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Analysis of Test Criteria for Specifying Foam Firefighting Agents for Aircraft Rescue and Firefighting

August 1994

Final Report

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16. Abstract

[illegible] quantities and application rates for FAA certified airports are based on [illegible] fire test data [illegible] Aqueous Film-Forming Foam (AFFF) and protein-based foams. [illegible] aircraft fuel fires in sixty seconds. Foam agents which are used [illegible] aviation applications should demonstrate this level of performance, [illegible] a safety factor which assures adequate performance under less than optimum [illegible].

A review [illegible] standard test methods and performance criteria indicates a wide range of [illegible]. The U.S. Military Specification (MIL SPEC) for AFFF, on which the [illegible] criteria was developed, is the most stringent in terms of extinguishment [illegible] density. However, no direct correlation has been demonstrated between many [illegible] required physical chemical properties tests and fire extinguishment/burnback [illegible].

It was demonstrated, using comparative data from numerous small- and large-scale fire tests, that the small-scale MIL SPEC fire tests correlate with large-scale test results. MIL SPEC agents, which provide a safety factor over minimum FAA requirements, also are [illegible] to have proportioning, storage, stability, and shelf-life attributes appropriate for crash rescue firefighting applications. Adoption of the MIL SPEC for AFFF agents is recommended. Future work related to foam testing should focus on the use [illegible] principles to establish fundamental foam extinguishment mechanisms.

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PREFACE

The intent of this work, performed by Hughes Associates, Inc., was to review available test data and regulations and standards related to foam agent performance. Based on this review, recommendations are made for appropriate specification for the Federal Aviation Administration (FAA) to adopt so that adequate performance is achieved when certified airports procure firefighting foam. The evaluation relied strictly on existing test data; no testing was performed specifically for this evaluation. The data include previously unpublished data of tests performed by George Geyer of the FAA, which was presented at the International Conference on Aviation Fire Protection, Interlaken, Switzerland, in September 1987. The contributions of Mr. Geyer, which also include much of the earlier, baseline data, are recognized.

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Advisory Circular
AFFF	Aqueous Film-forming Foam
ARFF	Aircraft Rescue and Firefighting
CFR	Crash Fire Rescue
FAA	Federal Aviation Administration
FFFP	Film Forming Fluoroprotein
FM	Factory Mutual
FP	Fluroprotein
FPF	Fluoroprotein Foam
FRDG	Fire Research and Development Group
ICAO	International Civil Aviation Authority
ISO	International Standards Organization
MIL SPEC	Military Specification
NFPA	National Fire Prevention Association
NRL	Naval Research Laboratory
PF	Protein Foam
PKP	Purple K Powder
QPL	Qualified Products List
SC	Spreading Coefficient
SRDB	Scientific Research and Development Branch
UL	Underwriters Laboratories, Inc.

EXECUTIVE SUMMARY

Federal Aviation Administration (FAA) and National Fire Protection Association (NFPA) primary foam agent requirements are based on the inherent philosophy that hydrocarbon fuel spill fires resulting from survivable aircraft crashes must be rapidly controlled and extinguished. This time frame, measured in seconds, includes notification, emergency response, and time to control/extinguish the fire. Success is based on the ability to limit this total response/suppression time to less than the time required for safe evacuation, which is primarily a function of the time to fuselage burnthrough when the crash airplane is intact.

Through large-scale testing and estimates of potential spill sizes as a function of aircraft size, minimum agent quantities and application rates have been established. For Aqueous Film-Forming Foam (AFFF), these quantities were based on FAA large-scale tests where Military Specification (MIL SPEC) Qualified Products List (QPL) agents or agents submitted for QPL evaluation were used. The 0.13 gpm/ft^2 (5.5 Lpm/m^2) application rate was based on these AFFF agents. Foams which are candidates for this application rate should be judged using this criteria.

A review of standard test methods and performance criteria indicates a wide range of requirements. Variations in test size, application rate, fuel, and nozzle placement make comparison between methods extremely difficult. Given these variations, it becomes difficult to judge agents based on a simple measure of performance and extinguishment application density. It was shown that the MIL SPEC, using a low flashpoint fuel and the lowest application rate of any test standard reviewed, requires the least amount of agent for extinguishment. The extinguishment application density for the International Civil Aviation Authority (ICAO), Underwriters Laboratories, Inc. (UL), and International Standards Organization (ISO) standards are respectively 2, 4, and 6 times that required for the MIL SPEC. The MIL SPEC is also explicit in its requirement that agents be a film former; other methods, with the notable exception of ICAO, now recognize the appropriateness of this requirement by including similar criteria. No direct correlation, however, has been established between chemical/physical properties criteria in the MIL SPEC and the fire extinguishment and burnback characteristics.

It has been demonstrated, using comparative data from the FAA and specific control time data from numerous fire tests, that criteria from the small-scale MIL SPEC AFFF tests correlate with large-scale data. Agents which meet the small-scale test criteria are able to meet NFPA and FAA control-time requirements at less than the design application rate. The limited data available suggest that agents that fail to meet the MIL SPEC criteria may not provide this same factor of safety. Given the basis of the FAA criteria (tests with QPL agents) and the critical time frames involved in ARFF operations (1-3 minutes to respond, 60 seconds to control the spill fire), this safety factor is entirely appropriate as a basis for minimum FAA certification.

The relevance of physical and chemical property tests in the MIL SPEC to ARFF applications has been well established over the years through testing designed to improve the MIL SPEC. These tests assure that AFFF has desirable attributes related to accurate proportioning, storage, stability, and shelf life in addition to minimum performance characteristics when used with other agents and when misproportioned. For FAA certification, one alternative would be to specify minimum fire performance requirements only. The risk is that QPL agent formulations may be modified, which might affect the overall impact of foam quality, e.g., half-strength performance, interagent compatibility, and Purple K

Powder (PKP) compatibility. A change in baseline agent performance would require reestablishment of the correlations demonstrated in this analysis, including large-scale testing. As a practical matter, it has been demonstrated that the majority of large airports already reference the MIL SPEC. For smaller airports, there may be some cost impact in referencing the entire MIL SPEC. However, it is precisely at these airports, with their limited equipment and training resources, where the factor of safety inherent in the MIL SPEC may be most important when it comes to an actual survivable aircraft crash incident.

The proliferation of standard test methods and various criteria for foams has not yielded significant benefits in our understanding of fundamental foam extinguishing mechanisms. This is shown by the lack of one-to-one correlation of specific tests (e.g., film formation, expansion, drainage, spreading coefficient, and fluorine content) with extinguishment and burnback performance. It is apparent that a single valid test method or combination of methods to evaluate all types of foam have yet to be developed. While a single test might be used, the variables involved leads to no clear correlatable distinction between individual foams and differences between foam types. This is another endorsement for adoption of the MIL SPEC for AFFF; it is, to date, the method with the best data to correlate results between small- and large-scale for the application of interest, FAA certification of primary agents at critical application rates.

It is recommended that the FAA adopt the MIL SPEC in its entirety as criteria for accepting foam agents used at the 0.13 gpm/ft^2 (5.5 Lpm/m^2) application rate. The UL 162 standard type 3 application test is adequate for agents used at the higher application rate of 0.20 gpm/ft^2 (8.2 Lpm/m^2) for fluoroprotein foam (FPF). Any future work related to foam testing should focus on the use of first principles to establish fundamental foam extinguishment mechanisms. The goal should be to correlate and use bench-scale results to predict large-scale performance.

BACKGROUND

Firefighting foams are the primary agents used at airports to combat fuel fires resulting from aircraft incidents. In the United States, the Federal Aviation Administration (FAA) certifies airport operations, including aircraft rescue and firefighting (ARFF) capabilities. Guidelines for facilities and agents are given in Advisory Circular (AC) 150/5210-6C, "Aircraft Fire and Rescue Facilities and Extinguishing Agents"[1]. Minimum quantities of agents are described, both in terms of total quantities and rates of application. Protein foams (PF) are required to be applied at 0.20 gpm/ft^2 (8.2 Lpm/m^2) while aqueous film-forming foams (AFFF) must be applied at 0.13 gpm/ft^2 (5.5 Lpm/m^2). This difference in application rate recognizes the inherent advantage of using AFFF in extinguishing hydrocarbon pool fires; AFFF has been demonstrated to extinguish pool fires more rapidly than protein foams at equivalent application rates[2]. For equivalent extinguishment times, lower rates of AFFF are required compared to protein foams. The National Fire Protection Association Standard 403, "Standard for Aircraft Rescue and Fire Fighting Services at Airports[3]," recognizes an application rate of 0.18 gpm/ft^2 (7.2 Lpm/m^2) for fluoroprotein foam (FPF).

The number and types of firefighting foams offered to FAA certified airports have proliferated. The distinction between foam types has been blurred with the introduction of fluoroprotein, film-forming fluoroprotein (FFFP), and alcohol-resistant foams. Airports require technical guidance for selecting appropriate agents. Currently, the FAA advisory circular only provides general guidance, e.g., Section 24 of AC 150/5210-6C:

> ". . . While it is recognized that acceptance testing of extinguishing agents is necessary, the technical characteristics, quality, stability, compatibility, etc., cannot be determined during such system tests or demonstrations. Therefore, the airport management should request that prospective bidders and suppliers of fire-extinguishing agents furnish indication of tests on performance and quality by a recognized laboratory."

The situation was further complicated when Underwriters Laboratories, Inc. (UL) approved FFFP as both a fluoroprotein and an AFFF agent in their listings. They have subsequently removed aircraft firefighting from the scope of their test standard, UL 162[4].

Certified airports must now individually determine the standard of performance to invoke when purchasing foam agents. The performance should relate to the level of safety established by the required foam application rates. Since large-scale fire testing by each individual airport is no longer a viable means of evaluation, smaller scale test methods must be utilized. The test method should demonstrate correlation with the large-scale test methods used to establish the baseline application rates. The referencing of a standard test method should also provide a degree of quality control in the purchase of agents which have demonstrated appropriate fire performance capability.

OBJECTIVE

The objective of this report is to document and analyze the existing data on the performance of foam agents. Based on this analysis, a technically based performance standard for commercial airport foam requirements is to be recommended for inclusion in an FAA Advisory Circular.

APPROACH

In order to identify appropriate foam standards, the basis for the foam application rates was identified. These application rates are based on the ability to control a fire before passengers in a survivable post-crash incident are threatened by an exterior pool fire. Having established the basis of the requirements, a review of test data was performed to identify important foam parameters. These data are drawn largely from FAA and Naval Research Laboratory (NRL) tests and evaluations. Test standards used in the United States and other countries were identified, including methods currently used by large U.S. airports. Using the large-scale data and small-scale test methods, an attempt was made to demonstrate correlation between small- and large-scale results. This includes data related to the issue of equivalency of FFFP with AFFF. Based on the analysis, recommendations were developed for adopting a standard method/criteria in the advisory circular and for performing additional research to develop a more technically sound method to determine important foam parameters.

HISTORICAL BASIS FOR FOAM REQUIREMENTS

THE SURVIVABLE POST-CRASH AIRCRAFT ACCIDENT.

A substantial amount of work has been conducted on the effects of pool fires on aircraft fuselages. The underlying principle is to temporarily maintain the integrity of an aircraft fuselage to allow passenger escape or rescue. Lindemann[5] has summarized the critical times for passenger survivability. When an aircraft is involved in a fuel spill fire, the aluminum skin will burnthrough in about one minute. If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt out in approximately three minutes. At that time, the cabin temperature rapidly increases beyond survivable levels. References 6, 7, and 8 provide additional research on the fuselage integrity issue.

ARFF vehicles are designed to reach an accident scene on the airport property in two to three minutes, depending on the standard enforced by the authority having jurisdiction. Having reached the scene in this time frame, the extinguishing agent must be applied to control a fire in one minute or less. The one-minute critical time for fire control is recognized by FAA, National Fire Prevention Association (NFPA), and the International Civil Aviation Authority (ICAO).

Minimum agent requirements on ARFF vehicles are established using the one-minute critical control time plus the anticipated spill area for the largest aircraft using the airport. A "theoretical critical fire area" has been developed, based on tests, which is defined as the area adjacent to the fuselage, extending in all directions to the point beyond which a large fuel fire would not melt an aluminum fuselage regardless of the duration of the exposure. Considering the function of the size of an aircraft, the theoretical critical fire area was refined to a practical critical fire area after the evaluation of actual aircraft fire incidents indicated that less agent was being used than the amounts developed from the theoretical fire area[9]. The practical critical area, two-thirds the size of the theoretical critical area, is widely recognized by the aviation fire safety community, including FAA, NFPA, and ICAO. Vehicles must be equipped with sufficient agent and discharge devices to control a fire in the practical critical area within one minute.

CRITICAL APPLICATION RATES.

Tests were conducted by the FAA to determine application rates for a single-agent attack to achieve fire control (e.g., 90 percent extinguishment of a fire area) within one minute under a wide variety of simulated accident conditions. Two concepts are important in addition to the application rate required for one-minute fire control: the critical application rate, below which fires will not be extinguished independent of the amount of time agent is applied; and application density, which is the amount of foam per unit area required to control or extinguish a fire.

Numerous fire tests were conducted in an attempt to quantify the important foam parameters. The basis for the current minimum application rates were originally developed by Geyer in tests of protein and AFFF agents[7]. These tests involved "modeling" tests with JP-4 pool fires of 70, 100, and 140 ft (21, 30, and 43 m) diameter. Large-scale verification tests with a B-47 aircraft and simulated shielded fires (requiring the use of secondary agents) were conducted with 110 and 140 ft (34 and 43 m) JP-4 pool fires. All tests were conducted with air-aspirating nozzles. The protein foam conformed to the Federal Specification, O-F-555b[10], while the AFFFs used were in nominal conformance with the Military Specification for AFFF. These tests were being performed at the time when the seawater compatible version of the AFFF MIL SPEC[11] had just been adopted based on large-scale tests[12]. The draft seawater AFFF specification described in reference 12 is the "father" of the current version of the MIL SPEC, MIL-F-24385 Rev. F[13].

Figure 1 shows the results of the "modeling" experiments. This shows that, for a control time of 60 seconds, the application rate for AFFF was on the order of 0.04 - 0.06 gpm/ft^2 (1.6 - 2.4 Lpm/m^2) while the application rate for protein foam was 0.08 - 0.10 gpm/ft^2 (3.3 - 4.1 Lpm/m^2). The data indicate that the application rate curves become asymptomatic at rates of approximately 0.1 gpm/ft^2 (4.1 Lpm/m^2) and 0.2 gpm/ft^2 (8.2 Lpm/m^2) for AFFF and protein foam respectively. Above these rates, fire control times would not appreciably improve. Likewise, critical application rates for fire control are indicated when control times increase dramatically. The single test with a fluoroprotein agent indicated that this agent, as expected, fell between AFFF and protein foam.

The large-scale auxiliary agent tests were conducted to identify increases in foam required when obstructed fires with an actual fuselage were added to the scenario. The results, shown in table 1, indicated that fire control times increased by a factor of 1 to 1.9 for AFFF and 1.5 to 2.9 for protein foams. It was estimated that the most effective foam solution application rates were 0.12 - 0.14 gpm/ft^2 (4.9 - 5.7 Lpm/m^2) for AFFF and 0.18 - 0.22 gpm/ft^2 (7.5 - 9 Lpm/m^2) for protein foam. This is the original basis of the recommendations adopted by ICAO[9] of 0.13 gpm/ft^2 (5.5 Lpm/m^2) for AFFF and 0.20 gpm/ft^2 (8.2 Lpm/m^2) for protein foam. These values are still used by the FAA, NFPA, and ICAO. When multiplied by the practical critical fire area, they form the basis of minimum foam flow rates and water requirements on Crash Fire Research (CFR) vehicles.

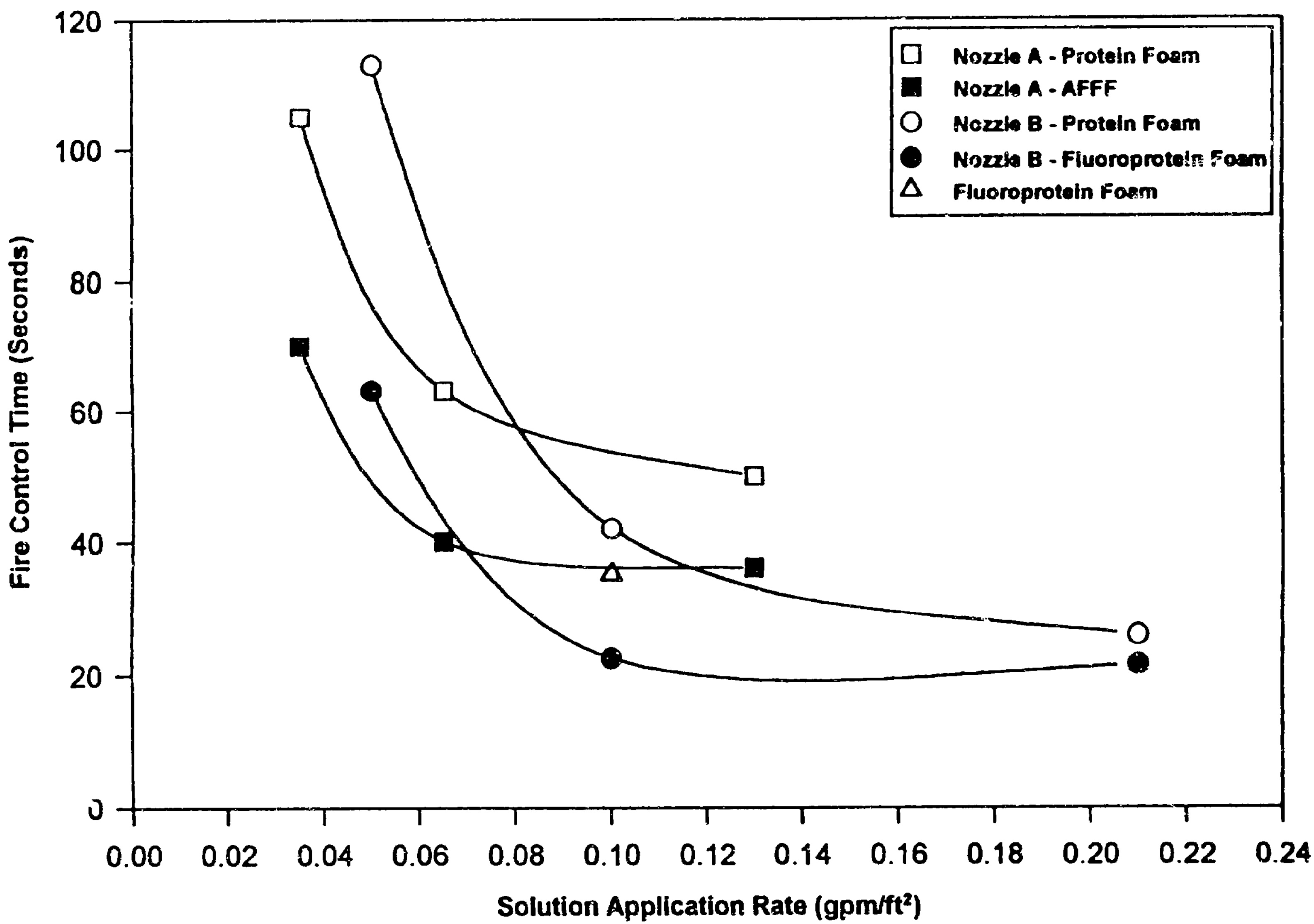

FIGURE 1. FIRE CONTROL TIME AS A FUNCTION OF SOLUTION APPLICATION RATE USING PROTEIN FOAM AND AFFF

TABLE 1. SUMMARY OF THE FIRE CONTROL TIMES USING THE B-47 AIRCRAFT

Equipment Approach	Test 1 Starboard Port Rear		Test 2 Starboard Port Rear		Test 3 Starboard Port Rear		Test 4 Starboard Port Rear	
Fire Diameter (ft (m))	140 (43)	140 (43)	140 (43)	140 (43)	110 (34)	110 (34)	110 (34)	110 (34)
Solution Rate (gpm (Lpm))	780 (2950)	780 (2950)	780 (2950)	780 (2950)	496 (1880)	530 (2010)	496 (1880)	530 (2010)
Solution Application Rate (gpm/ft^2 (Lpm/m^2)	0.10 (4.1)	0.10 (4.1)	0.10 (4.1)	0.10 (4.1)	0.10 (4.1)	0.11 (4.5)	0.10 (4.1)	0.11 (4.1)
Dispensing Equipment	Nozzle B	Nozzle B	Nozzle B	Nozzle B	Nozzle A	Foam Pump	Nozzle A	Foam Pump
Foam Agent	AFFF	AFFF	Protein	Protein	AFFF	AFFF	Protein	Protein
Fire Preburn Time - s	22	19.5	35	25	15	15	25	25
Fire Control Time After Ignition - s	76 front 68 rear	55 front 54 rear	80 front 80 rear	none	47 front 33 rear	58 front 43 rear	180 front 180 rear	145 front 140 rear
Average Fire Control Time After Ignition - s	70	54.5	80	none	40	50.5	180	142.5
Fire Control Time After Start of Foam - s	50 front 45 rear	35.5 front 34.5 rear	45 front 45 rear	none	22 front 18 rear	43 front 28 rear	155 front 155 rear	120 front 115 rear
Average Fire Control Time After Foam - s	48	35	45	none	25	35.5	155	117.5
Fire Damage to Fuselage Skin	Severe	Very minor	Severe	Severe	Minor	Severe	No data	No data
Control Time of Equivalent Pool Fires - s	23	23	40	40	34	30	55	38

Tests of AFFF alone were conducted by Geyer[14]. These agents, which were selected from the U.S. Qualified Products List (QPL) (MIL SPEC requirements), were tested on JP-4, JP-5, and aviation gasoline fires. Air-aspirating nozzles were used. The results are shown in figures 2 and 3. Similar data were collected by holding the JP-4 fuel fire size constant at 8000 ft^2 (743 m^2) and varying the flow rates to develop application rate comparisons. These data are shown in figure 4. The data show that Foam A is more effective than Foam B at lower application rates.

Additional tests were conducted by Geyer to verify the continuation of the reduction of water when AFFF agents were substituted for protein foam[15]. In 82.4-, 101-, and 143-ft (25, 31, and 44 m)-diameter Jet A pool fires, AFFF, fluoroprotein, and protein foams were discharged with aspirating and nonair-aspirating nozzles. Three and six percent concentrates were used. The six percent concentrates were manufactured in accordance with the MIL SPEC in force at the time. The three percent concentrates were not manufactured to the MIL SPEC since three percent concentrations were not yet included in the MIL SPEC. The data, summarized in figure 5, validated the continued allowance of a 30 percent reduction in water requirement at certified U.S. airports when AFFF is substituted for protein foam. A minimum application rate of 0.05 gpm/ft^2 and 0.10 gpm/ft^2 (2.0 and 4.1 Lpm/m^2) were identified for AFFF and PF/FPF respectively for controlling Jet A fires. This is consistent with earlier work. The data showed that nonair-aspirated AFFF was more effective at critical application rates than air-aspirated AFFF. This was verified by Jablonski[16] in tests with Air Force crash trucks as shown in table 2.

SUMMARY AND KEY FACTORS.

The historical test data clearly supports the philosophy that AFFF can be applied at rates lower than protein and fluoroprotein foams. Large-scale tests were used to develop the required application rates needed for critical one-minute fire control.

Where these tests used AFFF, the agents were from the QPL or the agents were in nominal conformance with the MIL SPEC, e.g., a developmental agent formulated to meet a new revision of the MIL SPEC. MIL SPEC AFFF forms the basis of the current FAA, NFPA, and ICAO criteria for reduced application rates and agent quantities.

The Montreal ICAO Panel[9] pointed out that quantities of agent required to extinguish actual aircraft fires are normally greater than those for test and training fires for a variety of reasons. They identified the problems of scaling from small to large scale, the training of the firefighting personnel, inaccessibility of some fire areas, initial overuse of foam, the three-dimensional nature of aircraft fires, and difficulties in deployment and control. Geyer has also identified wind as a factor. It is appropriate then, that any standard specifying foam products have a factor of safety This is usually accomplished by having tests meet fire performance and burnback requirements at critical application rates, i.e., at rates below the rate at which increases provide insignificant benefits. For AFFF, rates above 0.10 gpm/ft^2 (4.1 Lpm/m^2) may not provide any significant benefit in terms of substantially decreased control times. Critical rates for AFFF are on the order of 0.03 - 0.05 gpm/ft^2 (1.2 - 1.6 Lpm/m^2).

The issue is to select a test method which provides screening of good and poor products and establishes a factor of safety appropriate for aviation applications. The appropriate safety factor is dependent on the application. For combustible liquid and tank farm applications, which the UL Standard is geared towards, a fire incident may last days. The fire control time may not be critical compared to the need to provide extended burnback resistance. This compares to the seconds required for control of an

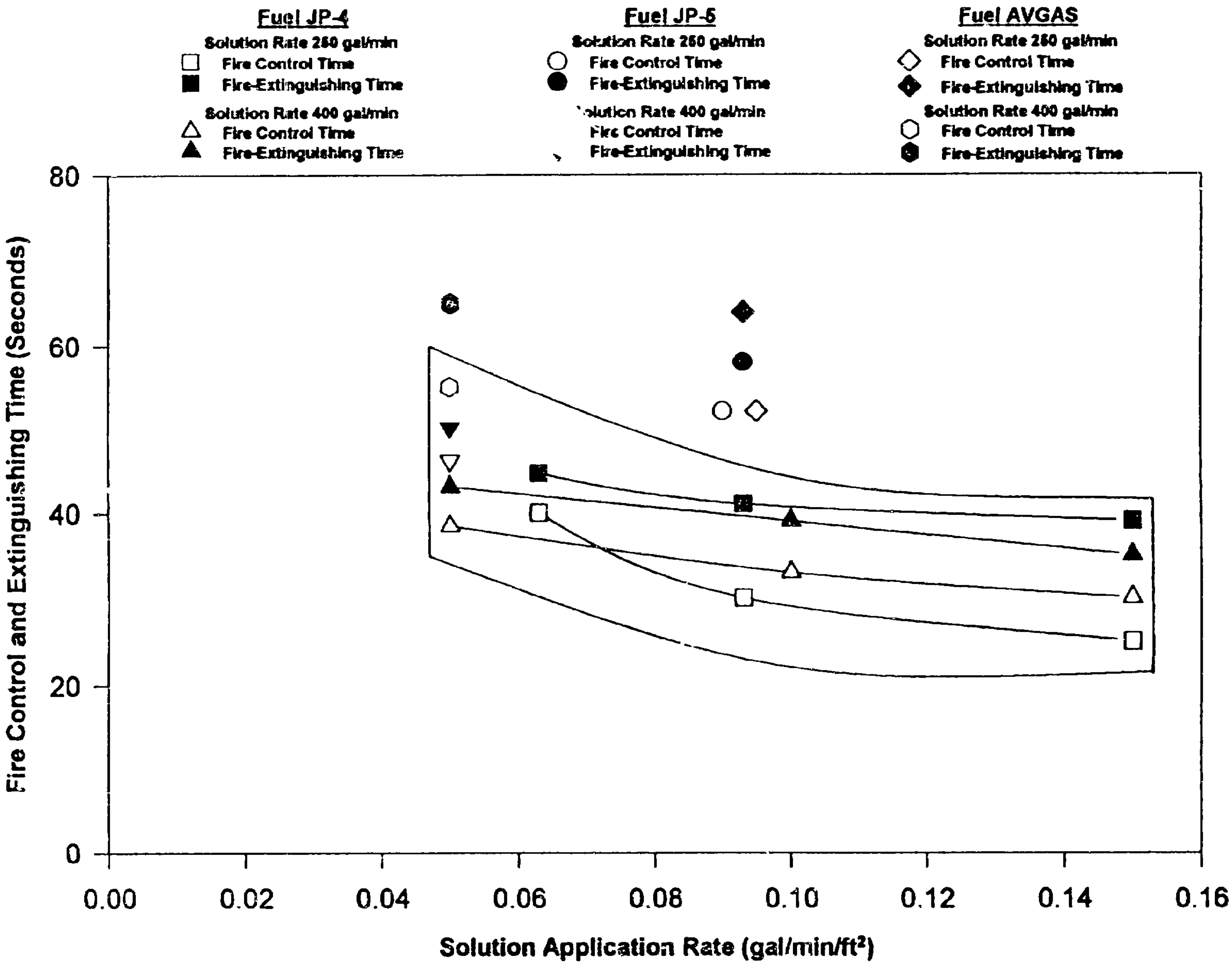

FIGURE 2. FIRE CONTROL AND EXTINGUISHING TIMES AS FUNCTIONS OF THE FOAM SOLUTION APPLICATION RATE USING MANUFACTURER A'S AFFF AGENT AT 250 AND 400 GAL/MIN ON JP-4, JP-5, AND AVGAS FIRES

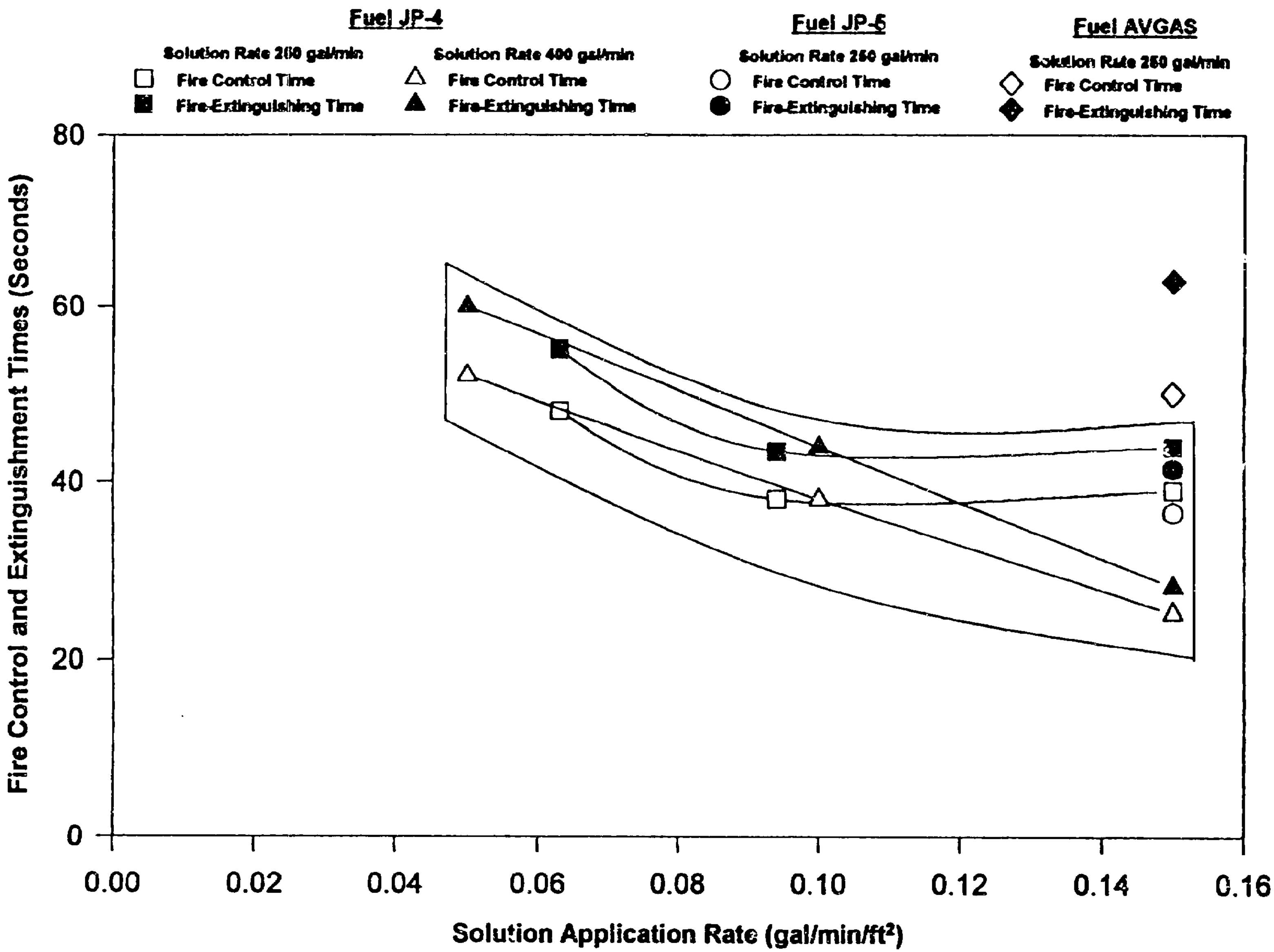

FIGURE 3. FIRE CONTROL AND EXTINGUISHING TIMES AS FUNCTIONS OF THE FOAM SOLUTION APPLICATION RATE USING MANUFACTURER B'S AFFF AGENT AT 250 AND 400 GAL/MIN ON JP-4, JP-5, AND AVGAS FIRES

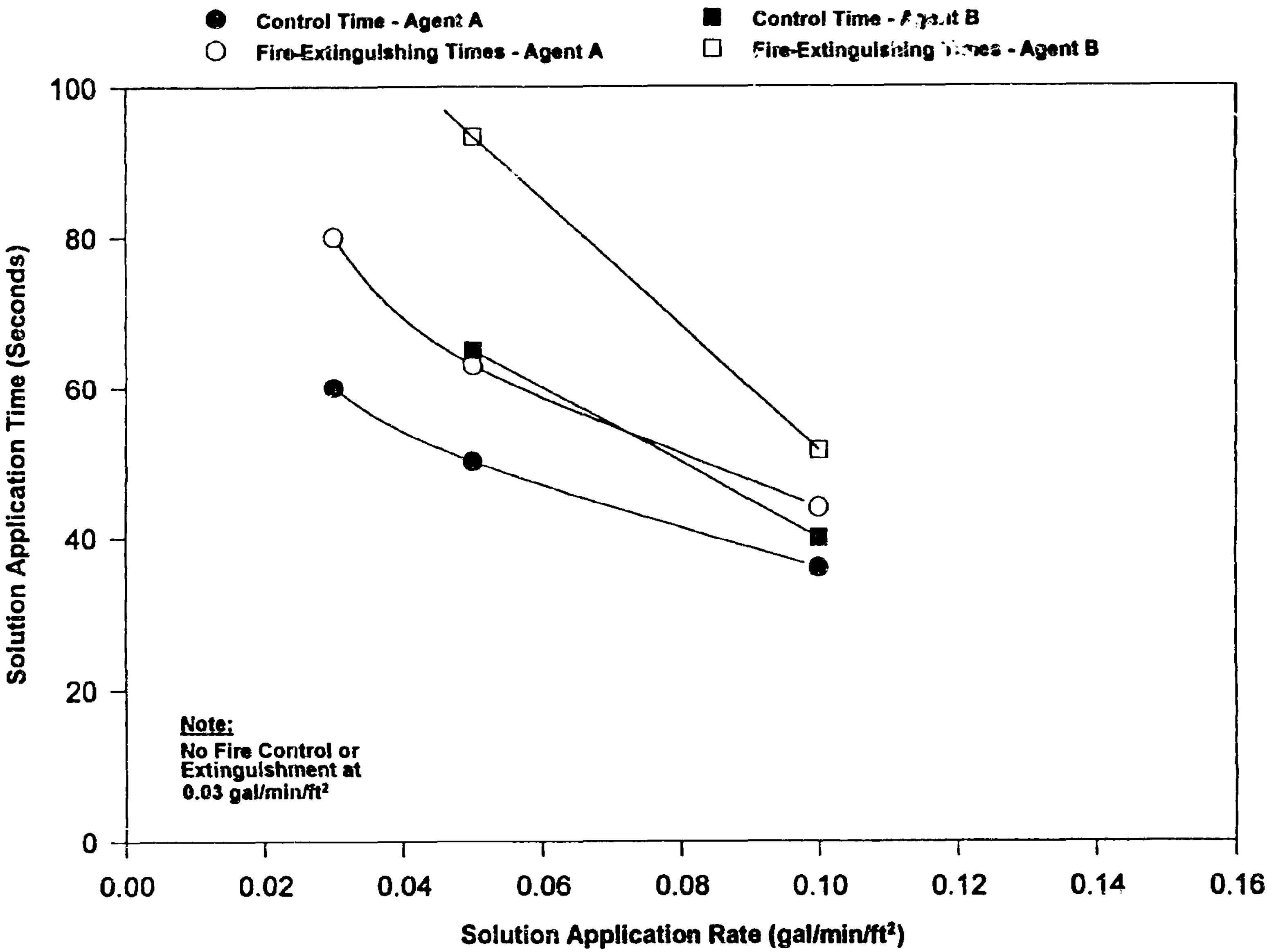

FIGURE 4. FIRE CONTROL AND EXTINGUISHING TIMES AS A FUNCTION OF SOLUTION APPLICATION RATE USING AFFF AT 250, 400, AND 800 GAL/MIN ON 8000 FT^2 JP-4 FUEL FIRES

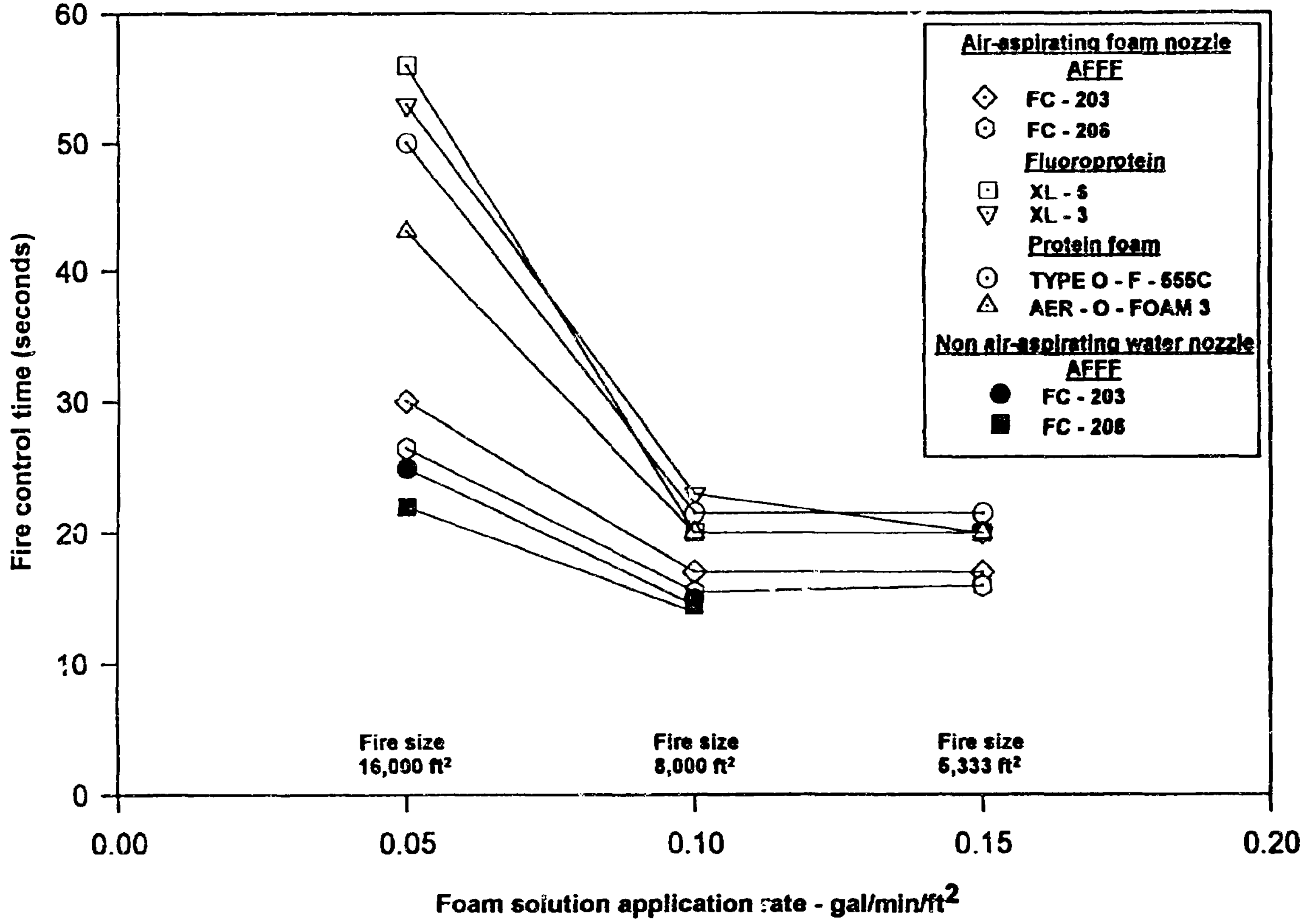

FIGURE 5. FIRE CONTROL TIME AS A FUNCTION OF SOLUTION APPLICATION RATE FOR AFFF, FLUOROPROTEIN, AND PROTEIN FOAMS FOR JET A FUEL FIRES

TABLE 2. SUMMARY OF FIRE TEST DATA FOR APPLYING AQUEOUS FILM-FORMING FOAM THROUGH AIR-ASPIRATING AND NONAIR-ASPIRATING NOZZLES

Test	Aircraft Mockup	Nozzle	AFFF Solution Rate (gpm (Lpm))	Fire Control 90 Percent Extinguishment: Time (s)	Fire Control 90 Percent Extinguishment: Density (gal/ft² (L/m²))	Burnback: Time to 25 Percent (min)	Burnback: Density (gal/ft² (L/m²))
Phase I – 250 gpm (946 Lpm) Air-aspirating and Non Air-aspirating Nozzles (MB-1 vehicle) on 4000 ft² (372 m²) JP-4 Fuel Fires							
1	No	Air-aspirating	260 (984)	31	0.033 (1.3)	12.3	0.059 (2.4)
2	No	Air-aspirating	267 (1010)	28	0.031 (1.3)	16.6	0.063 (2.6)
3	No	Nonair-aspirating	263 (995)	22	0.024 (0.98)	11.2	0.063 (2.6)
4	No	Nonair-aspirating	241 (912)	18	0.018 (0.73)	14.0	0.055 (2.2)
5	Yes	Air-aspirating	252 (954)	27	0.028 (1.1)	11.7	0.058 (2.4)
6	Yes	Air-aspirating	239 (905)	31	0.031 (1.3)	13.8	0.059 (2.4)
7	Yes	Nonair-aspirating	240 (908)	23	0.023 (0.94)	21.0	0.056 (2.3)
8	Yes	Nonair-aspirating	232 (878)	21	0.020 (0.81)	17.7	0.056 (2.3)
Phase II – Fire Test Data for Applying Aqueous Film-forming from 750 to 800 gpm (2839 to 3028 Lpm) Air-aspirating and Nonair-aspirating Nozzles on 8000 ft² (2440 m²) JP-4 Fuel Fires							
9	No	P-4 Air-aspirating	711 (2690)	37	0.055 (2.2)	15.5	0.121 (4.9)
11	No	P-4 Air-aspirating	671 (2540)	39	0.055 (2.2)	21.0	0.095 (3.9)
10	No	P-4A Nonair-aspirating	819 (3100)	40[a]	0.068[a] (2.8)	14.0	0.128 (5.2)
12	No	P-4A Nonair-aspirating	804 (3040)	27	0.045 (1.8)	18.0	0.116 (4.7)
13	Yes	P-4 Air-aspirating	715 (2710)	35	0.052 (2.1)	14.3	0.090 (3.7)
16	Yes	P-4 Air-aspirating	739 (2800)	34	0.052 (2.1)	12.8	0.120 (4.9)
14	Yes	P-4A Nonair-aspirating	823 (3120)	23	0.039 (1.6)	>28[b]	0.105 (4.3)
15	Yes	P-4A Nonair-aspirating	840 (3040)	23	0.040 (1.6)	16.5	0.107 (4.4)

[a] Equipment malfunction – water only for initial 20-second application
[b] Wind conditions affected test results

aviation incident a difference of several orders of magnitude compared to tank farm incidents. Differences in agent performance measured in seconds, which may normally be disregarded, have to be considered for aviation incidents.

The next sections describe different foam agents and address the issues of appropriate test standards, the meaning of small-scale test variables, the correlation of small- and large-scale tests, and the appropriate approach the FAA should pursue.

DESCRIPTION OF AGENTS.

As described in the previous section, foam agents were tested in large scale to develop extinguishing application rates and quantities. Fluoroprotein foams were assigned an application rate between AFFF and protein foam by NFPA. The development of new foams, particularly FFFP and alcohol-resistant foams, do not necessarily fit in the standard categorization of AFFF, protein, or fluoroprotein foams. This raises the question of where new formulations should fit in the application rate requirements.

An understanding of the composition of foam agents is fundamental to an evaluation of the issue. Geyer et al.[15] having described the composition of various foam agents, paraphrased as follows:

- Protein Foam (PF) protein foam is a "mechanical" foam produced by combining (proportioning) foam concentrate and water at specific ratios. The resulting solutions are then discharged through a mixing chamber. The mixing chamber introduces (aspirates) air which expands the solution to create foam bubbles. The liquid concentrate consists primarily of hydrolyzed proteins in combination with iron salts. Hoof and horn meal, and hydrolyzed feather meal are examples of proteinaceous materials used in protein foam concentrates. When applied to a hydrocarbon fuel surface, the foam bubbles act to exclude the air from the fuel vapors, effectively preventing the creation of a combustible mixture. The bubbles also contain water to cool the fuel and attendant hot surfaces. No aqueous film is formed on the fuel surface with this type of agent.

- Fluoroprotein (FPF) - these agents are basically protein foams with fluorocarbon surface-active agents added. The varying degrees of performance are achieved by using different proportions of the base protein hydrolyzates and the fluorinated surfactants. While fluoroprotein foams generally have good fuel shedding capabilities and dry chemical compatibility, the solution which drains out from the expanded foam does not form a film on hydrocarbon fuels. However, the addition of the fluorinated surfactants may act to reduce the surface tension of the solution. This reduction may in turn decrease the viscosity of the expanded solution, thus promoting more rapid fire control when compared to protein foams.

- FFFP - these agents are also based on protein foam formulations. They are produced by increasing the quantity and quality of the fluorocarbon surfactants added to the protein hydrolyzate. By doing this, the surface tension of the resulting solution which drains from the expanded foam is reduced to the point where it may spread across the surface of a liquid hydrocarbon fuel. Under these conditions, the agent may still be termed a "fluoroprotein" foam, but the physical and fire extinguishing characteristics are similar and perhaps even equal to those of an AFFF (figure 6).

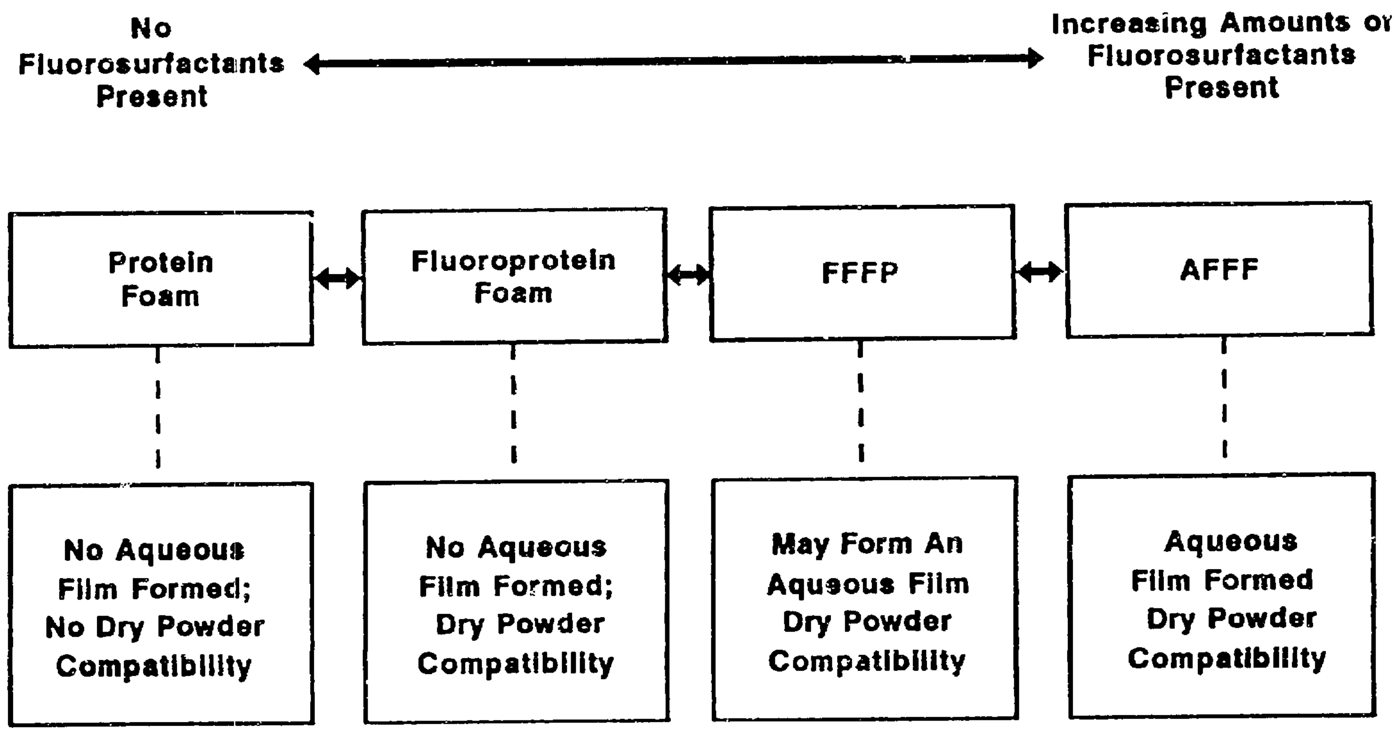

FIGURE 6. RELATIONSHIP OF VARIOUS TYPES OF FOAM AGENTS WITH RESPECT TO FLUOROSURFACTANT CONTENT, FILM FORMATION CAPABILITIES, AND DRY POWDER COMPATIBILITY

- AFFF - these agents are synthetically formed by combining fluorine free hydrocarbon foaming compounds with highly fluorinated surfactants. When mixed with water, the resulting solution achieves the optimum surface and interfacial tension characteristics needed to produce a film which will spread across a hydrocarbon fuel. The foam produced from this agent will extinguish in the same water cooling and vapor-excluding fashion as other foams. However, the solution which results from normal drainage or foam breakdown will quickly produce an aqueous "film" which spreads rapidly and is highly stable on the liquid hydrocarbon fuel surface. It is this film formation characteristic which is the significant feature of AFFFs.

These descriptions show that there are distinct chemical differences between protein based foams and AFFFs. The formulation of an FFFP may imply a simple mixing of a fluoroprotein agent with an AFFF. In fact, informal experiments have been performed where AFFFs were mixed with protein based foams[17,18]. The investigators found that this simplification ignores the chemical compatibility and synergistic effects of combined agents. For example, the source and proportions of proteinaceous materials in protein type foams is very important. Mixing protein based materials with AFFF may, under certain conditions, result in hydrolysis, deactivation of the protein, or a change of pH. While both investigators were able to achieve favorable results by mixing agents in the laboratory, neither recommend the practice for actual firefighting agents. Fiala[18] indicated that this procedure is "believed to be of no importance for practical use."

In general, the surfactants used in aqueous foams are long chained compounds which have a hydrophobic (water hating or water insoluble) group at one end and a hydrophilic (water loving or water soluble) group at the other end[19]. The molecular structure of a typical AFFF fluorinated surfactant is shown in figure 7. In this molecule, the perfluorooctyl group on the left is the hydrophobic group, while the propyltrimethylammonium group is the hydrophilic group. When these compounds are dissolved into solution with water, they will tend to group near the surface of the solution and aligned so that their hydrophobic ends are facing towards the air/solution interface. The advantage of this is that the perfluorooctyl group found in these compounds is oliophobic (oil or hydrocarbon insoluble) as well as hydrophobic[20].

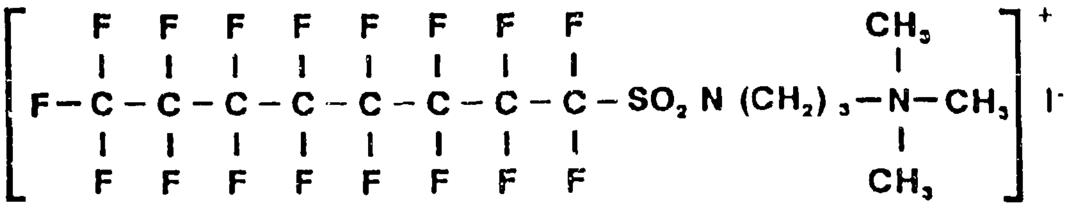

FIGURE 7. TYPICAL AFFF FLUOROSURFACTANT MOLECULE

AFFF concentrates also contain hydrocarbon surfactants. These compounds are less hydrophobic than those containing the perfluorooctyl group[21]. However, they do provide greater stability once the solution is expanded into a foam. The net result of combining both of these compounds in an aqueous solution is that the surface tension of the solution is reduced below that of water; the expanded foam produced from the solution is resistive to breakdown from heat, fuels, or dry chemical extinguishing agents, and the solution which drains out from the expanded foam is able to form a film on hydrocarbon fuels.

The importance of both the film formation and foam bubble characteristics of AFFF, resulting from the combination of fluorocarbon and hydrocarbon surfactants was evaluated in early work by Tuve et al.[22]. When a highly expanded stiff formulation of AFFF was used, these experimenters found it difficult to obtain good fire extinguishment and vapor sealing characteristics because the foam resisted flow and drainage of the aqueous solution (film) was slow. This was corrected by reducing foam expansion. Foam agent with an expansion ratio of eight-to-one and a 25 percent drainage time of six minutes appeared to offer the best compromise in characteristics. It provided a readily flowable foam which sealed up against obstructions, promoted the rapid formation of a surface-active film barrier on the fuel, and provided a sufficiently stable foam to resist burnback.

Chemical composition is vital in achieving a balanced formulation. This formulation must create a stable foam bubble which will, over time, release an aqueous solution with the ability to form a vapor suppressing film on hydrocarbon fuels. The introduction of FFFP is yet another chemical variant of the essential balanced formulation. Because foam matrix stability is also affected by the degree of aspiration of the foam solution, the continuing conflict over foam aspiration is naturally a related issue.

Having identified that chemical composition and foam quality are important factors in the equivalence debate, the issue can be simplified to one of fire performance capabilities. The best agent is the one that controls and extinguishes hydrocarbon fuel fires the fastest and provides the great. st degree of resistance to burnback. If agents are similar in terms of these fire performance criteria, then the user must judge if the other differences are important. This assumes that other operational requirements are met, e.g., the compatibility of the agent with CFR equipment and auxiliary agents.

STANDARDS AND REGULATIONS

NATIONAL STANDARDS AND TEST METHODS.

Given the differences in chemical composition between agents, how does the user select an agent? In the United States, the primary method of selecting agents is by reference to an UL listed product[23] or in the case of AFFFs, reference to the military specification, MIL-F-24385[13]. It was noted in the Background Section that the FAA does not have specific test criteria for foam agents.

The NFPA Standards and Recommended Practices related to aviation are contained in the following documents:

- NFPA 402M - Manual for Aircraft Rescue and Firefighting Operational Procedures (1989 Edition).
- NFPA 403 - Standard for Aircraft Rescue and Firefighting Services at Airports (1993 Edition).

- NFPA 412 - Standard for Evaluating Aircraft Rescue and Firefighting Foam Equipment (1993 Edition).

- NFPA 414 - Standard for Aircraft Rescue and Firefighting Vehicles (1984 Edition).

These four standards are all closely related and in fact reference each other in many cases. NFPA 403 is the reference document in terms of foam requirements for crash, firefighting, and rescue operations. The CFR requirements in NFPA 402M, 412, and 414 are derived from NFPA 403. It is NFPA 403 which defines the minimum requirements for airport CFR services. Airports are categorized by the maximum size of aircraft serviced. The amount of apparatus and the minimum total extinguishing agent flow rate is then defined based on this categorization. Acceptable types and quantities of agents are described. These rates and quantities are based on the "critical fire area" concept described in the Historical Basis section. The membership of NFPA recently voted to adopt fire test criteria for primary extinguishing agents (foam) in NFPA 403. These new requirements and the rationale for adopting the test method are described in the correlation section of this report.

In order to determine the types of agents being used and methods of procurement, a survey of 24 major U.S. airports was conducted in 1990[24]. All of these facilities are classified as Index 5-8 airports in accordance with NFPA 403. Essentially, these airports require the greatest degree of protection in terms of CFR vehicle capability and agent capacity. Fire department personnel and/or procurement specialists were asked what foam concentrate they had most recently purchased. They were also asked how the foam agent was specified, e.g., by UL listing, MIL SPEC approval, or commercial specification.

The results of the survey are shown in table 3; complete details are contained in reference 24. The results of the survey were as follows:

1. All major airports use AFFF

   - 10 (42 percent) use 6 percent AFFF
   - 14 (58 percent) use 3 percent AFFF

2. Six airports (25 percent) supplement AFFF with another type of agent

   - 4 (17 percent) use fluoroprotein or protein foam
   - 2 (8 percent) use FFFP/Polar Solvent agents

     - Boston Logan (Mass. Port. Auth.) uses Angus Tridol 6 percent, which is a UL listed AFFF; they also carry Angus Petroseal 6 percent, an unlisted FFFP, on their apparatus in 5 gal. cans

     - San Diego uses both MIL SPEC AFFF and a UL listed dual-purpose agent (Angus Alcoseal, FFFP listed for use on both polar solvent and hydrocarbon fuels)

3. Fifteen (63 percent) reference the MIL SPEC

4. Five (21 percent) reference UL

TABLE 3. RESULTS OF AIRPORT FIRE DEPARTMENT FOAM USE AND SPECIFICATION SURVEY[a]

Airport Location	Foam Type				Specification		
	AFFF 6 %	AFFF 3 %	Fluoroprotein or Protein	Other	MIL SPEC	UL	Other
1. Atlanta	X					X	
2. BWI		X	X		X		
3. Boston	X			X			X
4. Chicago O'Hare		X					X
5. Cincinnati		X			X		X
6. Cleveland		X				X	X
7. Dallas/Fort Worth	X				X		
8. Denver		X			X		
9. Detroit	X		X				X
10. Dulles	X				X		
11. Houston (Intercontinental)	X				X		X
12. LAX		X			X		
13. Las Vegas		X			X	X	X
14. Miami	X		X				X
15. Nashville		X					X
16. Washington National	X				X		
17. New York Port Authority (JFK, Laguardia & Newark)		X			X		
18. Philadelphia		X	X		X		X
19. Phoenix		X			X		
20. San Diego	X			X	X	X	
21. San Francisco	X				X		
22. Seattle		X				X	X
23. St. Louis		X			X		
24. Tampa		X					X

[a] See Reference 24 for notes to this table.

5. Twelve (50 percent) use other methods in addition to or in lieu of MIL SPEC/UL requirements:

- Four airports (17 percent) use their own spec (Chicago, Cincinnati, Houston and Philadelphia)

- Four airports (17 percent) specify the manufacturer (Boston/MPA, Detroit, Tampa, and Nashville)

- FAA, Factory Mutual (FM) and NFPA "requirements" were also cited

The most significant finding was that the majority of the airports surveyed referenced the MIL SPEC.

INTERNATIONAL STANDARDS.

The number of international standards developed for foams is quite substantial. A brief review of the literature yielded over 17 different standards and test methods. These are summarized in table 4. While it is beyond the scope to individually review each document, it is important to note that most of the AFFF standards and specifications require either a film formation test and/or a positive spreading coefficient. Developments by the Eu.opean community are reviewed here since they are some of the strongest proponents of FFFP.

TABLE 4. EXAMPLES OF INTERNATIONAL SPECIFICATION TESTS FOR FOAM

	Type of Foam
United States/North America	
UL 162	All types
MIL-F-24385	AFFF
OF 555	Protein
28GP74 (Canada)	AFFF
Europe	
DT 8188/STNA/DGCA (France)	All types
FR 1-1007 (UK)	All types
Defence Standard 42-21 (UK)	Protein
Defence Standard 42-24 (UK)	AFFF
Defence Standard 42-22 (UK)	Fluoroprotein
ICAO Annex 14/Airport Services Manual	All types
ISO (proposed)	All types
Defense Standard DIN 14-272 (Germany)	AFFF
Specification N.FS60201 (France)	AFFF and fluoroprotein
NORDTEST NT FIRE 023 (Finland/Sweden, e.g., Swedish Civil Aviation Administration)	All types
Others	
DCA/E/2381 (Australia)	Protein
W5FE 7508, Issue No. 2 (Australia)	AFFF
Defense Standards 5603A (Australia)	AFFF
Department of Aviation WS FF 7508 (Australia)	AFFF
AFFF Specification (Japan)	AFFF
AFFF Specification (India)	AFFF

The ICAO develops crash firefighting and rescue documents for its member bodies. The *Airport Services Guide*, Part 1 -- Rescue and Firefighting (Third Edition, 1990) describes airport levels of protection to be provided (chapter 2) and extinguishing agent characteristics (chapter 8). Chapter 2, in describing minimum usable amounts of extinguishing agents, describes two levels of performance: Level A and Level B. The amounts of water specified for foam production are predicated on an application rate of 0.20 gpm/ft^2 (8.2 Lpm/m^2) for Level A and 0.13 gpm/ft^2 (5.5 Lpm/m^2) for Level B. Level B agents require less agent. Foam specifications are contained in chapter 8, table 8-1. These criteria are reproduced here as table 5. Foams meeting performance Level B have an extinguishment application density of 0.061 gal/ft^2 (2.5 L/m^2). Surface tension, interfacial tension, and spreading coefficient criteria in the previous edition of the Airport Services Guide have been deleted from table 8.

TABLE 5. ICAO FOAM TEST REQUIREMENTS

Fire Tests	Performance Level A	Performance Level B
1. Nozzle (air-aspirated)		
(a) Branch pipe	"UNI 86" foam nozzle	"UNI 86" foam nozzle
(b) Nozzle pressure	100 psi (700 kPa)	100 psi (700 kPa)
(c) Application rate	0.10 gpm/ft^2 (4.1 Lpm/m^2)	0.06 gpm/ft^2 (2.5 Lpm/m^2)
(d) Discharge rate	3.01 gpm (11.4 Lpm)	3.01 gpm (11.4 Lpm)
2. Fire size	$\cong$30 ft^2 ($\cong$2.8 m^2) (circular)	$\cong$48 ft^2 ($\cong$4.5 m^2) (circular)
3. Fuel (on water surface)	Kerosene	Kerosene
4. Preburn time	60 s	60 s
5. Fire performance		
(a) Extinguishing time	$\leq$ 60 s	$\leq$ 60 s
(b) Total application time	120 s	120 s
(c) 25% reignition time	$\geq$ 5 min	$\geq$ 5 min

The International Organization for Standardization has issued a draft specification for low-expansion foams, ISO/DIS 7203 (1992).[25] The specification includes definitions for protein, fluoroprotein, synthetic, alcohol resistance, AFFF, and FFFP concentrates. A positive spreading coefficient is required for film-forming foams when cyclohexane is used as the test fuel. There are toxicity, corrosion, sedimentation, viscosity, expansion, and drainage criteria. The fire test uses a 2.4-m-diameter circular pan with heptane as the fuel. The UNI 86 nozzle is used for either a "forceful" or "gentle" application method at a flow rate of 3 gpm (11.4 Lpm). The application rate is 0.06 gpm/ft^2 (2.4 Lpm/m^2). For the greatest performance level, a three-minute extinguishment time is required. This results in an extinguishment application density of 0.19 gal/ft^2 (7.6 Lpm/m^2)

The requirements for extinguishing and burnback are summarized in table 6. There are three levels of extinguishment performance and four levels of burnback performance. For extinguishing performance, Class I is the highest class and Class III the lowest class. For burnback resistance, Level A is the highest level and Level D the lowest level. Foam concentrates can be compared for each factor separately but not necessarily in combination. For example, a IC concentrate is superior to a ID or a

IIC concentrate, but it is not possible to say that it is superior to a IIB concentrate since it is superior in extinguishing performance but inferior in burnback resistance.

Typical performance classes and levels for different concentrates are provided. Typical anticipated performance for AFFF is noted as ID and for FFFP as IA/B. For alcohol resistant foams, both AFFF and FFFP are typically IA.

TABLE 6. MAXIMUM EXTINCTION TIMES AND MINIMUM BURNBACK TIMES FROM PROPOSED ISO SPECIFICATION

Extinguishing performance class	Burnback resistance level	Gentle application test		Forceful application test	
		Extinction time (min.) not more than	Burnback time (min.) not less than	Extinction time (min.) not more than	Burnback time (min.) not less than
I	A	not applicable		3	10
	B	5	15	3	not tested
	C	5	10	3	not tested
	D	5	5	3	not tested
II	A	not applicable		4	10
	B	5	15	4	not tested
	C	5	10	4	not tested
	D	5	5	4	not tested
III	B	5	15	not tested	not tested
	C	5	10	not tested	not tested
	D	5	5	not tested	not tested

PERFORMANCE FIRE TESTS.

The previous sections outlined requirements for foams in terms of the recognition of AFFF and FFFP, minimum application rates, and references to performance standards. Reference 24 provides additional details on NFPA requirements. Particularly in the NFPA standards, performance requirements are dictated in terms of "listing" and approval by the "authority having jurisdiction." Currently at U.S. airports, the airport managers are effectively the authority having jurisdiction in terms of foam specification. As shown in the airport survey, the U.S. AFFF Military Specification was the predominant performance specification referenced. Previous NFPA references to "listing" effectively translated to UL listing in accordance with UL 162, when applied to North America. Therefore, these two standards are evaluated here.

UL STANDARD 162. UL 162, "Standard for Foam Equipment and Liquid Concentrates," is the principle test standard for the listing of foam concentrates and equipment in the United States. Test procedures outlined in this standard have been developed to evaluate specific agent/proportioner/discharge device combinations. When a foam concentrate is submitted for testing, it must be accompanied by the discharge devices and proportioning equipment with which it is to be listed. These devices do not necessarily have to be manufactured by the foam vendor submitting the agent to be tested. Listed products are then described in the UL *Fire Protection Equipment Directory*. Each listing includes the discharge and proportioning devices with which the agent was tested.

UL defines foam liquid concentrate as either a protein or synthetic based agent that is intended to be diluted with fresh water, salt water, or a mixture of both fresh and salt water to a concentration of 1 percent or higher. Different types of low-expansion liquid concentrates are defined as follows:

1. AFFF - A liquid concentrate that has a fluorinated surfactant base plus stabilizing additives.

2. Protein - A liquid concentrate that has a hydrolyzed protein base plus stabilizing additives.

3. Fluoroprotein - A liquid concentrate that is similar to protein type concentrate, but with one or more fluorinated surfactant additives.

4. FFFP - A liquid concentrate that has both a hydrolyzed protein and fluorinated surfactant base plus stabilizing additives.

5. Synthetic - A liquid concentrate that has a base other than fluorinated surfactant or hydrolyzed protein.

Foam liquid concentrates, as noted, are not listed as agents alone. Listed with a system, they are associated with discharge devices classified as Type I, II, or III. Type I devices deliver foam gently onto the flammable liquid fuel surface, e.g., a foam trough along the inside of a tank wall. Type II discharge devices deliver foam onto the liquid surface in a manner which results in limited submergence of the foam below the fuel surface and restricted agitation at the fuel surface. Examples include subsurface injection systems, tank wall mounted foam chambers, and applications where foam is bounced off the wall of a tank. Type III discharge devices deliver foam directly onto the liquid surface and cause general agitation at the fuel surface, e.g., hand held nozzles. The flammable liquid fire tests in the UL 162 standard include methods for sprinklers, subsurface injection, and topside discharge devices, including nozzles.

The Class B fire tests for topside discharge devices are described in section 15 of UL 162. Commercial grade n-heptane is placed in a square test pan. The area of the pan is a minimum of 50 ft^2 (4.65 m^2). For Type III applications, the test nozzle is positioned above the test pan. The nozzle may be moved throughout the duration of foam application or fixed in position for part or all of the application. The application rates ("densities" in the UL Standard) for various concentrates are outlined in table 7. Film forming fluoroprotein concentrates are required to pass the fire extinguishment and burnback tests at both application rates.

TABLE 7. FOAM APPLICATION RATES AND TORCH EXPOSURE TIMES IN UL 162 FOR HYDROCARBON FUELS

Concentrate	Application Rate (gpm/ft^2 (Lpm/m^2))	Time of Foam Application (min)	Maximum Extinguishment Density (gal/ft^2 L/m^2))	Duration of Torch Testing (min)
Protein, fluoroprotein, film-forming fluoroprotein[a], or synthetic concentrate	0.06 (2.4)	5	0.3 (12.2)	15
Aqueous film-forming or film-forming fluoroprotein[a] concentrate	0.04 (1.6)	3	0.12 (4.9)	9

(a) Film-forming fluoroprotein is to be tested at application rates of 0.06 and 0.04 gpm/ft^2.
From UL 162, Sixth edition

After the fuel has been added to the test pan, the nozzle arranged, and the liquid concentrate flow rate determined, the fuel is ignited. The resulting fire is allowed to burn for a 60-second preburn time. At the end of the 60-second preburn, foam is discharged for the duration specified in table 7. The foam blanket resulting from the foam discharge must spread over and completely cover the fuel surface, and the fire must be completely extinguished before the end of the foam discharge period.

After all of the foam is discharged, the foam blanket formed on top of the fuel is left undisturbed for the period specified in table 7. During the time the foam blanket is left undisturbed, a lighted torch is passed approximately 1 inch (25.4 mm) above the entire foam blanket in an attempt to reignite the fuel. The fuel may not reignite, candle, flame, or flashover while the torch is being passed over the fuel. However, candling, flaming, or flashover that self-extinguishes is acceptable provided that the phenomenon does not remain in one area for more than 30 seconds.

After the attempts to reignite the fuel with the lighted torch are completed, a 12-in-diameter (305 mm) section of stovepipe is lowered into the foam blanket. The portion of the foam blanket that is enclosed by the stovepipe is removed with as little disturbance as possible to the blanket outside the stovepipe. The cleared fuel area inside the stovepipe is ignited and allowed to burn for 1 minute. The stovepipe then is slowly removed from the pan while the fuel continues to burn. After the stovepipe is removed, the foam blanket must either restrict the spread of fire for 5 minutes to an area not larger than 10 ft^2 (0.9 m^2), or flow over and reclose the burning area.

A standard test nozzle is not specified. Rather, a test nozzle is used which has foam expansion and drainage values equivalent to those produced with the full-scale nozzle submitted as part of the system being evaluated. The full-scale nozzle is then listed with the concentrate. This test method was originally developed for testing protein foams which used air-aspirating devices. Despite the subsequent inclusion of AFFFs, the method is still geared to evaluate air-aspirated devices. This is evidenced in a recent listing of AFFF and FFFP concentrates. Only one combination which uses a nonaspirating nozzle was identified in the UL Directory: Elkhart Brass Model HF-350 and HF-500 nozzles with 3M FC-600 ATC proportioned at 3 percent. No nonaspirating monitors or rooftop CFR turrets of any type are listed with AFFF or FFFP concentrates.

This is a serious limitation with regard to CFR applications. Nonair-aspirated hand line nozzles, used in conjunction with air-aspirated and nonair-aspirated roof and bumper turrets, are the predominant foam discharge devices used in CFR applications in the United States. This limitation was recognized by UL; they have dropped references to CFR applications in the Scope of the Sixth Edition of the UL 162 Standard, effective March 7, 1989.

Because UL 162 is not an agent specification, there are no requirements for physical properties, such as film formation and sealability, corrosion resistance, and spreading coefficient. Neither are there any provisions to test, on a large scale, the degree of dry chemical compatibility of an agent, or the effects of aging or mixing with agents of another manufacturer. However, it should be noted that UL is considering such requirements. In particular, requirements for a positive spreading coefficient (greater than zero using cyclohexane) for film-forming foams have been proposed and are being implemented.[26]

U.S. MILITARY SPECIFICATION. The US Military Specification, MIL-F-24385, is the AFFF procurement specification for the U.S. Military and Federal Government. The US military, in all likelihood, is the largest user of foam in the world. The inherent and primary purpose of the specification is to obtain a product which will rapidly control and extinguish hydrocarbon fuel fires. It is important to recognize that it is a procurement specification as well as a performance specification. As a result, there are also requirements for packaging, initial qualification inspection, and quality conformance inspection. Equipment designs unique to the military, in particular U.S. Navy ships, also impact on the specification requirements (e.g., use of seawater solutions and misproportioning related fire tests). Nevertheless, by its very design it exacts a high level of fire extinguishment performance. It addresses not only fire extinguishment and burnback requirements, but important chemical and physical properties as well. These requirements have been developed based on research and testing at the Naval Research Laboratory and actual operational experience with protein and film forming foams.

Table 8 summarizes the important fire extinguishment, burnback resistance, film formation, and foam quality requirements established by the AFFF MIL SPEC. The fire tests are conducted using 28 ft^2 (2.6 m^2) and 50 ft^2 (4.6 m^2) circular fire test pans. There are specific requirements to conduct a fire test of the agent after it has been subjected to an accelerated aging process (simulating prolonged storage) and after intentionally misproportioning the concentrate with water. In particular, the requirement to conduct a fire test of the agent at one-half of its design concentration is one of the most difficult tests. The 28 ft^2 (2.6 m^2) half-strength fire test must be extinguished in 45 seconds, only 15 seconds greater than allowed when the full-strength solution is used.

The physical and chemical properties evaluated for MIL SPEC agents are outlined in table 9, along with the rationale for each test. These procedures have been developed based on experience and specific military requirements. Some of these requirements obviously have relevance to CFR applications. For example, the MIL SPEC requires that the agent be compatible with dry chemical agents. Dry chemical agents may be used as "secondary" agents in CFR, e.g., to combat three dimensional fuel fires, where AFFF may have limited effectiveness. Specifically, the MIL SPEC requires that an agent's compatibility with potassium bicarbonate dry chemical agent (PKP) be determined. The burnback time of the foam in the presence of the dry chemical is measured. Also, the concentrate of one manufacturer must be compatible with concentrates of the same type furnished by other manufacturers, as determined by fire tests and accelerated aging tests.

TABLE 8. SUMMARY OF THE U.S. MILITARY AFFF SPECIFICATION (MIL-F-243 85, REVISION F) KEY PERFORMANCE REQUIREMENTS

Test Fuel	Revision F
Fire Extinguishment	
28 ft^2 (2.6 m^2) fire test	
Application rate	0.071 gpm/ft^2 (2.9 Lpm/m^2)
Maximum extinguishment time	30 s
Maximum extinguishment density	0.036 gal/ft^2 (1.45 L/m^2)
50 ft^2 (4.6 m^2) fire test[a]	
Application rate	0.04 gpm/ft^2 (1.6 Lpm/m^2)
Minimum 40-second summation	320 s
Maximum extinguishment time	50 s
Maximum extinguishment density	0.033 gal/ft^2 (1.34 L/m^2)
Fire Extinguishment -- Over and Under Proportioning (28 ft^2 (4.6 m^2) Test)	
Half strength	
Maximum extinguishment time	45 s
Maximum extinguishment density	0.054 gal/ft^2 (2.2 L/m^2)
Quintuple (5x) Strength[b]	
Maximum extinguishment time	55 s
Maximum extinguishment density	0.066 gal/ft^2 (2.7 L/m^2)
Burnback Resistance	
28 ft^2 (2.6 m^2) fire test	25% maximum at 360 s[b]
50 ft^2 (4.6 m^2) fire test	25% maximum at 360 s
Foam Quality	
Expansion ratio	6.0 : 1 minimum
25% drainage time	150 s minimum
Film Formation	
Spreading coefficient	
Fuel	Cyclohexane
Minimum value	3
Ignition resistance test	
Fuel	Cyclohexane
Pass/fail criteria	No ignition

[a] Salt water only.
[b] 300 s for half-strength solutions; 200 s for quintuple-strength solutions

TABLE 9. PHYSICAL/CHEMICAL PROPERTIES AND PROCUREMENT REQUIREMENTS OF THE AFFF MIL SPEC

Requirement	Rational
Refractive Index	enable use of refractometer to measure solution concentrations in field; this is most common method recommended in NFPA 412
Viscosity	assures accurate proportioning when proportioning pumps are used; e.g., balanced pressure proportioner or positive displacement injection pumps
pH	assures concentrate will be neither excessively basic or acidic; intention is to prevent corrosion in plumbing systems
Corrosivity	limits corrosion of and deposit buildup on metallic components (various metals for 28 days)
Total Halides/Chlorides	limits corrosion of and deposit buildup on metallic components
Environmental Impact	biodegradability, fish kill, BOD/COD; assures an environmentally safe product
Accelerated Aging	film formation capabilities, fire performance, foam quality; assures a long shelf life
Seawater Compatibility	assures satisfactory fire performance when mixed with brackish or salt water
Interagent Compatibility	allows premixed or storage tanks to be topped off with different manufacturers' agents without affecting fire performance
Reduced and Over Concentration Fire Test	assures satisfactory fire performance when agents are proportioned inaccurately
Compatibility with Dry Chemical (PKP) Agents	assures satisfactory fire performance when used in conjunction with supplementary agents
Torque to Remove Cap	able to remove without wrench
Packaging Requirements	strength, color, size, stackable, minimum pour and vent opening tamper proof seal; assures uniformity of containers and ease of handling
Initial Qualification Inspection	establish initial conformance with requirements
Quality Conformance Inspection (each lot)	assures continued conformance with requirements

Also included are requirements related to corrosivity, pH, concentrate viscosity, total halides, and environmental impact (e.g., biodegradability). Detailed packaging requirements are included, again developed based on experience in handling the product. For example, the maximum torque of the container cap is specified so that the cap can be removed by hand. This assures rapid agent transfer for refilling operations in an emergency. In addition to the initial qualification approval and inspection, a quality conformance inspection of each lot of agent must be performed. The manufacturer is currently permitted to submit certified data for quality conformance. Having met requirements of the MIL SPEC, agents are listed on the QPL[27], published by the U.S. Department of Defense.

TEST RESULTS

FAA TESTS.

LABORATORY AND SMALL-SCALE TESTS. George Geyer of the FAA has performed the most detailed comparative analysis to date on foam agents relative to performance. Preliminary results were presented at the International Conference on Aviation Fire Protection in Interlaken, Switzerland, in September 1987[28]. The summary data were made available for this report; the actual test notes and data were not available for review. Twenty-four agents, including alcohol-type foams, were evaluated. Agents were classified as PF, FPF, FFFP, and AFFF. In addition to fire tests, the chemical composition, spreading coefficients and expansion, and drainage characteristics of foam agents were evaluated.

Fire tests, 50 ft^2 (4.6 m^2) in size, were conducted in accordance with both the AFFF MIL SPEC, Revision C and UL 162. The discharge rate and resulting application rate was modified to produce higher rates for the protein based nonfilm-forming agents. Average results of these tests are summarized in tables 10 to 13. The data indicate that AFFFs, as a group, have better control, extinguishment, and burnback characteristics compared to FFFPs. Fourteen AFFF agents were evaluated. Disregarding the Ansul ARC and the National Aer-O-Water tests having an application rate greater than 0.04 gpm/ft^2 (1.6 Lpm/m^2), the range of control and extinguishment times are 19-39 seconds and 36-63 seconds respectively for AFFFs. The range of 25 percent burnback times is 345-564 seconds. The data show that there is a range of performance for AFFF concentrates. The control and extinguishment times for the FFFP agents tested were 34-43 seconds and 53-74 seconds respectively. Twenty-five percent burnback ranged from 241-423 seconds. The average control, extinguishment, and burnback times for the QPL AFFF agents were 22, 43, and 436 seconds, respectively, compared to average control, extinguishment, and burnback times of 39, 59, and 356 seconds for the FFFP agents.

The differences in foam agent performance are shown graphically in figure 8, which is a comparison of representative agents using the MIL SPEC and UL test methods. The trends in the data remain essentially the same, independent of the test method. AFFFs perform better than FFFPs, which in turn perform better than FPs in terms of fire control and extinguishment. The differences in control and extinguishment times between the tests methods may be attributed to differences in the pan configuration and method of foam application. The MIL SPEC uses a round pan around which the firefighter may move, while UL 162 uses a square pan and the fire fighter must remain stationary while applying the agent. It should be noted that the QPL products were not evaluated in this comparison.

As part of a related analysis of physical and chemical properties, Geyer attempted to establish correlations between agent spreading coefficient and fire performance. Spreading coefficient values were first determined for six agents, each on three different fuels. The same agents were then subjected to 50 ft^2 (4.6 m^2) MIL SPEC fire tests using each test fuel. The results showed that no direct correlation existed between spreading coefficient and extinguishment performance of the agents tested.

TABLE 10. FIRE PERFORMANCE OF AFFF CONCENTRATES ON MIL SPEC 50 ft^2 (4.6 m^2) FIRE TEST CONDUCTED BY FAA

Concentrate	Percent Proportioning	Application Rate (gpm/ft^2 (Lpm/m^2))	Control Time (s)	Extinguish Time (s)	40 s Summation (%)	25% Burnback (s)	Spreading Coefficient vs. Cyclohexane
3M Lightwater FC 206 CE[a]	6	0.04 (1.6)	20	36	346	485	3.01
3M Lightwater FC 203 CE[a]	3	0.04 (1.6)	25	42	333	428	4.74
3M Lightwater FC 201	1	0.04 (1.6)	21	43	348	503	2.01
3M Lightwater ATC FC 600	3	0.04 (1.6)	20	42	342	564	2.86/2.86
Angus Tridol 6%	6	0.04 (1.6)	25	45	323	397	4.40
Angus Tridol 3%	3	0.04 (1.6)	39	63	275	345	5.20
Ansul Ansulite AFC3 6%[a]	6	0.04 (1.6)	24	44	331	495	3.40
Ansul Ansulite AFC3A 3%[a]	3	0.04 (1.6)	23	46	329	422	4.29
Ansul Ansulite 1%	1	0.04 (1.6)	26	43	318	463	4.00
Ansul Ansulite ARC	3	0.04 (1.6)	70	92	58	288	5.24/3.94
National Aer-O-Water 6%	6	0.04 (1.6)	22	37	340	450	2.22
National Aer-O-Water 3%	3	0.04 (1.6)	29	55	286	365	4.57
National Aer-O-Water 3%[a] Military 3%	3 3 3	0.04 (1.6) 0.06 (2.4) 0.10 (4.1)	19 20 17	47 32 27	341 354 365	352 614 637	4.56
National Aer-O-Water Universal	3	0.04 (1.6)	36	60	270	434	5.12/5.07

[a] Military QPL product

TABLE 11. FIRE PERFORMANCE OF FILM-FORMING CONCENTRATES CONDUCTED BY FAA

Concentrate	Percent Proportioning	Application Rate (gpm/ft^2 (Lpm/m^2))	Control Time (s)	Extinguish Time (s)	40 s Summation (%)	25% Burnback (s)	Spreading Coefficient vs. Cyclohexane
Angus Petroseal 6%	6	0.04 (1.6)	43	61	228	423	4.00
Angus Petroseal 3%	3	0.04 (1.6)	34	53	240	404	2.60
National Aer-O-Film 3%	3	0.04 (1.6)	40+	74	245	241	4.14

TABLE 12. FIRE PERFORMANCE OF FLUOROPROTEIN FOAM CONCENTRATES CONDUCTED BY FAA

Concentrate	Percent Proportioning	Application Rate (gpm/ft^2 (Lpm/m^2))	Control Time (s)	Extinguish Time (s)	40 s Summation (%)	25% Burnback (s)
Angus FP 570 6%	6	0.06 (2.4)	98	258	100	711
Angus FP 70 3%	3	0.06 (2.4)	112	240	118	549
Angus Alcoseal 3%/6%	3	0.06 (2.4)	45	84	153	341
National Aer O-Foam XL6 6%	6	0.06 (2.4)	98	174	138	741
National Aer-O-Foam XL3 3%	3	0.06 (2.4)	85	161	130	787

TABLE 13. FIRE PERFORMANCE OF PROTEIN FOAM CONCENTRATES CONDUCTED BY FAA

Concentrate	Percent Proportioning	Application Rate (gpm/ft^2 (Lpm/m^2))	Control Time (s)	Extinguish Time (s)	40 s Summation (%)	25% Burnback (s)
Angus Nicerol 6%	6	0.10 (4.1)	80	181	160	225
Angus Nicerol 3%	3	0.10 (4.1)	70	None	145	--

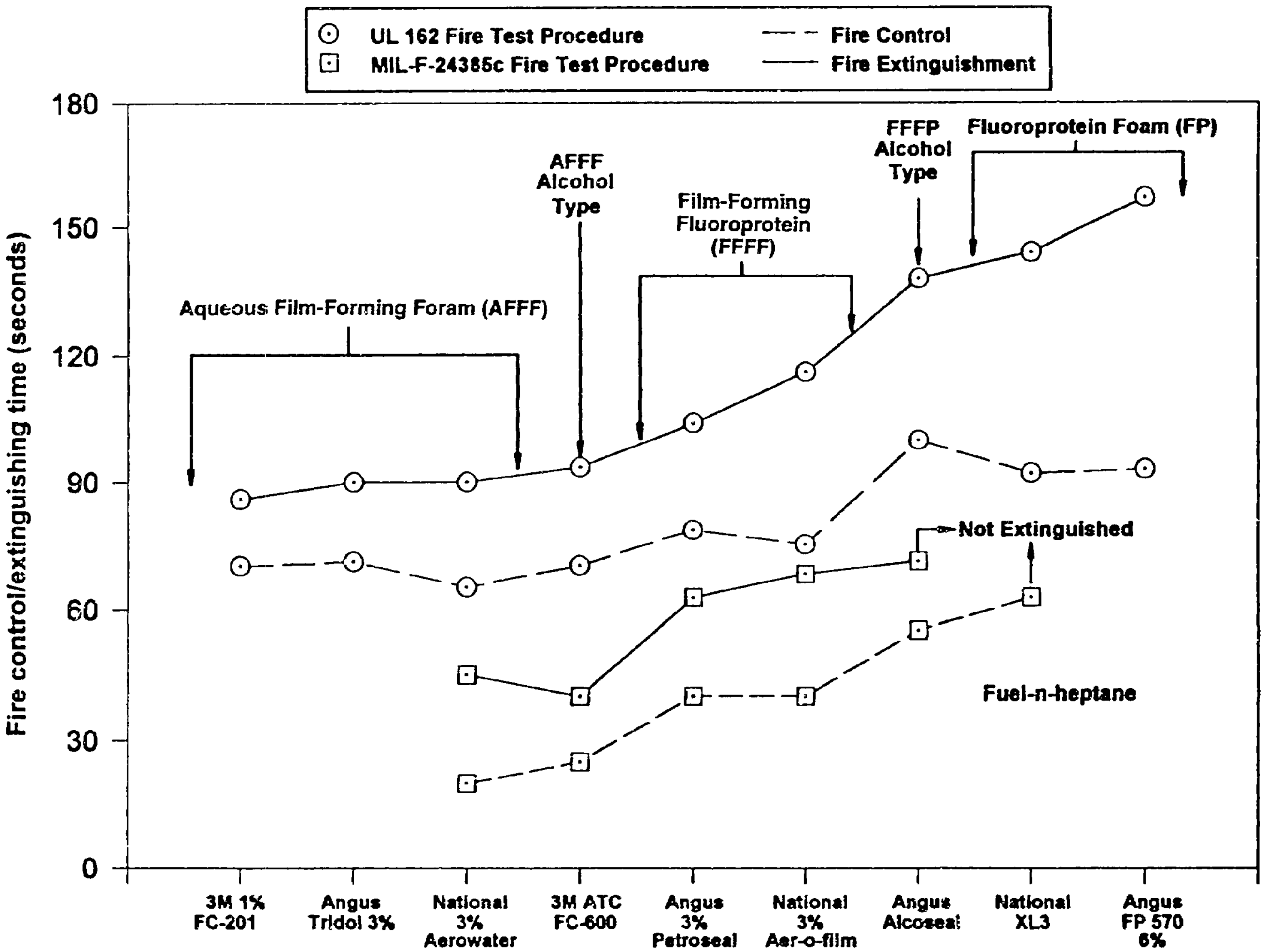

FIGURE 8. SUMMARY OF 50 FT^2 (4.6 M^2) FIRE TESTS, FROM FAA TESTS [28]

This can be seen from tables 10 and 11, where spreading coefficients and extinguishing data are shown for the 50 ft^2 (4.6 m^2) fire tests. Revision C of the MIL SPEC requires a minimum spreading coefficient of 3 using cyclohexane as the test fuel. There are agents listed in tables 10 and 11 which exceed this criteria (Angus Tridol 3 percent, National Aer-O-Water 3 percent, Angus Petroseal 6 percent), but do not pass the 50 ft^2 (4.6 m^2) extinguishment criteria of 50 seconds. Likewise, agents with a spreading coefficient less than three were able to meet the extinguishment limit (3M FC 201, 3M ATC FC 600, National Aer-O-Water 6 percent).

Additional data on physical/chemical parameters from the FAA tests and the effects of test fuels are contained in appendix A.

LARGE-SCALE TESTS. The principle objective of the large fire tests conducted by FAA was to evaluate those agents which demonstrated the most rapid fire control and extinguishing times using the MIL-F-24385C and Underwriters Laboratories, Inc., UL 162 test methods. The results of the 50 ft^2 (4.6 m^2) fire tests performed in accordance with the MIL SPEC are contained in the previous section. Based upon these data, two 3 percent type film-forming foam agents were selected. One agent was an AFFF manufactured to conform with the military specification (Ansul 3 percent). The second agent was a commercial FFFP agent listed by UL (Petroseal Angus Fire Armour).

The fire test bed was a 79 ft (24 m) square (6241 ft^2, 516 m^2) diked fire area in one corner of which an additional 50 ft (15 m) square (2500 ft^2, 232 m^2) fire pit had been constructed. The first series of tests was performed in the 2500 ft^2 (232 m^2) fire pit, after which the dikes were removed before conducting the second series of tests in the 6241 ft^2 (576 m^2) fire pit. During the tests, all foam solutions were discharged at the rate of 250 gpm (950 Lpm), which provided application rates of 0.04 and 0.10 gpm/ft^2 (1.6 and 4.1 Lpm/m^2) to the fire surface. These rates were within the known threshold values for aqueous film-forming foams as shown previously in figure 5.

Both fire pits were initially charged with sufficient water to provide a smooth water-based substrate upon which Jet A (0.35 gal/ft^2, 14.2 L/m^2) aviation fuel could be floated. A preburn period of 30 seconds was allowed after complete involvement of the fuel surface was obtained before initiation of the fire extinguishing operation. The nozzle was positioned on the upwind side of the active fire pit and operated by an experienced firefighter committed to extinguishing the fire as rapidly as possible.

Two different foam nozzles were employed in the experiments. One nozzle was a single-barrel air-aspirating unit (National Foam P/N BC-31B) with a nominal solution discharge rate of 250 gpm (950 Lpm) at 100 psi (690 kPa). The second nozzle was a short-barrel nonair-aspirating unit (Valpariso IN 46383 Task Force Tip). The average foam quality produced by each nozzle using the NFPA 412 foam test method, expansion ratio and 25 percent solution drain time, is shown in table 14.

The results of the fire tests are summarized in figure 9. Two large-scale tests were performed at an application rate of 0.04 gpm/ft^2 (1.6 Lpm/m^2) using the air-aspirating nozzle, and four at the rate of 0.10 gpm/ft^2 (4.1 Lpm/m^2), employing both the air-aspirating and nonair-aspirating nozzles.

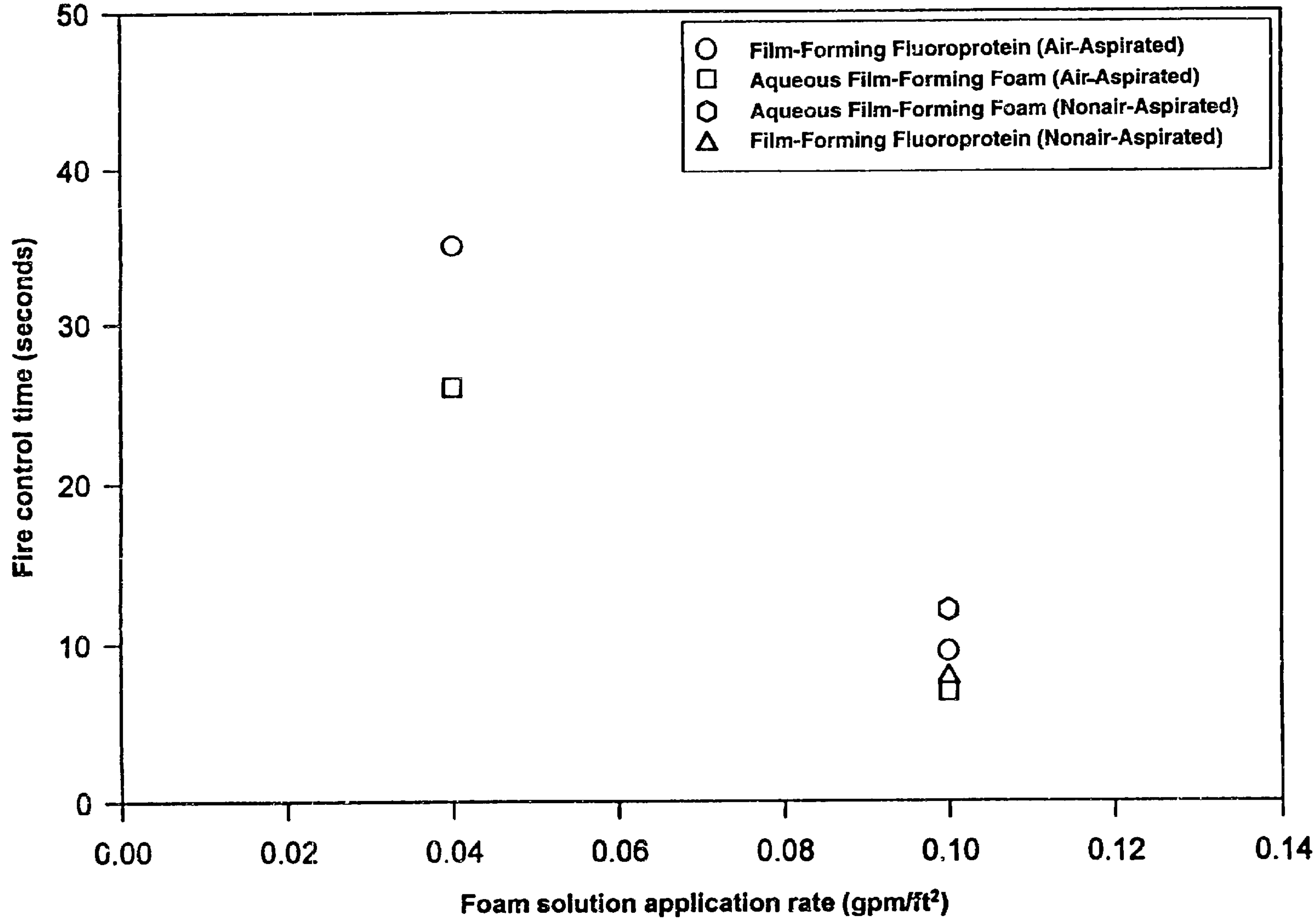

FIGURE 9. FIRE CONTROL FOR LARGE-SCALE FIRE TESTS OF FFFP AND AFFF

TABLE 14. FOAM QUALITY FOR LARGE-SCALE AFFF/FFFP TESTS

Agent	Type percent	Average Solution Concentration %	Expansion Ratio		Solution Drain Time 25% (s)	
			Air-aspirated	Nonair-aspirated	Air-aspirated	Nonair-aspirated
AFFF	3	2.8	6.7 : 1	4.9 : 1	191	86
FFFP	3	2.6	5.8 : 1	5.0 : 1	199	108

The average fire control times obtained for FFFP and AFFF on Jet A fuel fires were essentially equal at a solution application rate of 0.10 gpm/ft^2 (4.1 Lpm/m^2). The difference in control times between the air-aspirating and nonair-aspirating nozzles is not significant. This indicates that the threshold or critical application rate was exceeded by both agents. When the solution application rate was reduced from 0.10 to 0.04 gpm/ft^2 (4.1 to 1.6 Lpm/m^2), the time for fire control for AFFF was nine seconds less than that for the FFFP. The control times in the 6240 ft^2 (516 m^2) tests with the lower application rate were in good agreement with the control times from the 50 ft^2 (4.6 m^2) MIL SPEC tests (tables 10 and 11).

NRL TESTS.

Because of the wide variation in the fire test data reported in the literature, a series of comparative fire and bench-scale laboratory tests with FFFP and AFFF concentrates were performed by the Naval Research Laboratory[24]. Bench-scale tests were performed according to the MIL SPEC (Revision C) test procedures, including spreading coefficient, film formation and sealability characteristics, fluorine content, expansion ratio, and 25 percent drainage time. The spreading coefficient test was described earlier. The film formation and sealability test is a fundamental bench-scale test which confirms that the agent is in fact able to produce a film on the fuel surface. It also indicates whether or not the film will seal vapors against ignition. Fluorine content is used to judge the amount of fluorinated surfactant present in the agent. Expansion ratio and 25 percent drainage time are physical measurements which determine the quality of the foam produced.

Fire tests were conducted using the 28 ft^2 (2.6 m^2) and 50 ft^2 (4.6 m^2) MIL SPEC test methods. Motor gasoline was used in both tests; n-heptane was also used in the 50 ft^2 (4.6 m^2) test. To make a preliminary assessment of the FFFP with a nonair-aspirated discharge device, an ad hoc test was performed comparing nonair-aspirated agents.

A manufacturer of FFFP products supplied a sample for testing. The two AFFF products used were both 6 percent agents qualified under Revision C of the AFFF MIL SPEC. They were obtained from the Navy supply system.

Test methods followed the MIL SPEC Revision C criteria, except where n-heptane was substituted as a test fuel. Complete results are detailed in reference 24 and summarized in appendix B.

The AFFF had higher surface tensions and lower interfacial tensions compared to the FFFP. The FFFP had a negative spreading coefficient when tested with n-heptane. No across-the-board correlations between spreading coefficients and fire control, extinguishment, and burnback resistance were apparent.

Likewise, there were no direct correlations between fluorine content and fire performance. Average fire control, extinguishment, and burnback times were better for the MIL SPEC AFFF agents compared to the FFFP in all test situations, with greater differences observed when n-heptane was used as the test fuel in the 50 ft^2 (4.6 m^2) test.

The overall results were in agreement with the results from the FAA tests. The MIL SPEC AFFF had better fire extinguishment and burnback performance compared to FFFP. No direct correlations between fire extinguishment and burnback performance and the small-scale spreading coefficient, film and seal, and expansion and drainage tests were observed. Yet, the film-forming agents formulated to the MIL SPEC consistently yielded better fire control and burnback performance.

OTHER FIRE TESTS.

In order to assess the performance differences of FFFP compared to AFFF, a review of existing test data was performed[24]. Because FFFP is a relatively new product, there was limited small- and large-scale test data available compared to the considerable amount of data available for protein, fluoroprotein, and AFFF products. A detailed description of the literature and test data review is presented in reference 24.

It is extremely difficult to analyze the results from the literature on a one-to-one basis. Aside from the problems in relating different fire test methods, a more fundamental problem occurs in distinguishing individual foam concentrates. For example, it is widely accepted that AFFF concentrates which are formulated by a given manufacturer to meet the MIL SPEC may be a different formula than that submitted by the same manufacturer for UL listing. Furthermore, a manufacturer may have different formulas for the international market than for the U.S. domestic or military markets. The so-called "quality" of an agent may also be a function of the manufacturers' primary market. A vendor whose primary market is AFFF may devote more resources for different AFFF "blends" to serve different markets. Alternately, a vendor whose market is derived primarily from fluoroprotein concentrates may market AFFF only as needed, e.g., to provide "complete" service. Rarely are these differences distinguished in the literature and available test reports. It is uncommon to find the lot number and date of manufacture of foam concentrate reported in test data found in the literature.

These factors explain, in part, the findings of the literature review. In some cases, the AFFFs are shown to be generally better than FFFPs . In other cases, FFFPs are shown to be equal to or even better than AFFF. The data reviewed in reference 24 clearly show that all AFFFs are "not created equal", i.e., do not have the same control and fire extinguishing performance. Likewise, the data also show that all FFFPs are not equal in performance.

An example of the difficulty in assessing data where MIL SPEC or QPL agent is not specified is evident in the literature published by the Scientific Research and Development Branch (SRDB) of the Home Office of the United Kingdom. They have performed one of the few referencable test series on FFFP[29]. The objective was to assess suitable foams for hose reel systems for control and extinguishment of Class B fires. The agents tested included fluoroprotein, AFFF, and FFFP agents. Alcohol-type FFFP and AFFF agents were also tested. Gasoline (petrol) fires in a 431 ft^2 (40 m^2) circular fire test area were extinguished with the hose reel system flowing 26.5 gpm (100 Lpm). The effective application rate was 0.061 gpm/ft^2 (2.5 Lpm/m^2). Tests were conducted using aspirated and nonaspirated hose reel nozzles. After fire extinguishment, burnback tests were performed. The test report provides details on the test setup, procedure, and equipment. Data from the large-scale tests are summarized in table 15. The data show that the AFFF and FFFP agents tested had essentially equivalent fire control and extinguishment performance. When used with the aspirating nozzle, the FFFP had a greater average burnback time. The author concludes that all agents tested gave poor performance, both for extinguishment and burnback resistance, when applied through the nonaspirating device.

In two regards, these tests contradict the massive amount of data in the tests conducted with AFFF: the extinguishment density required to extinguish hydrocarbon pool fires and the use of nonair-aspirated AFFF for handline operations. The control extinguishment densities in table 14 are three times the densities achieved for control large-scale test fires reported by FAA (figure 9) and two to three times the application densities reported in the literature review in the Historical Basis section (appendix C).

The issue of air aspiration and the apparent advantages on nonair-aspirated AFFF were also described earlier. The authors conclude that, at least for the aspiration issue (which also contradicted earlier SRDB tests), very low nozzle aspiration (e.g., less than NFPA 412 recommendations) may be the problem. The issue of the high extinguishing densities remains unanswered. It may be an agent, fuel, or discharge device issue.

More recently, the Fire Research and Development Group (FRDG) in the United Kingdom performed comparative foam tests[30]. The data are summarized in table 16. A 602-ft^2 (56 m^2)-circular fire using lead-free petrol was extinguished using an air-aspirating nozzle discharging at 60 gpm (225 Lpm). The application rate was 0.1 gpm/ft^2 (4 Lpm/m^2). Commercial foams readily available in the United Kingdom were used, but there was no indication whether the concentrates met any specific performance test criteria (e.g., a UL-type test). Foams were also tested at reduced strength. The average 90 percent control times (51 s) of the two AFFF products were slightly better than the control times for the FFFP concentrates (58 and 63 s). In particular, one AFFF product performed very poorly when reduced to half strength. The author has previously expressed concern that the proposed ISO/CEN specification would not distinguish performance differences at reduced concentrations.[31] The author notes that the results show that large variations in performance can be expected from different products of the same foam type.

CORRELATION BETWEEN SMALL- AND LARGE-SCALE FIRE TEST RESULTS

SMALL-SCALE TEST PARAMETERS AND VARIABLES.

The previous sections described the variation in test methods, the results of common small-scale tests, and the development of aviation foam criteria based on large-scale results. Table 17 outlines the variables associated with foam performance and testing. As shown, there are an incredible number of variables associated with foam performance. These include factors involving foam bubble stability and fluidity, actual fire test parameters (fuel, nozzle, application rate), and environmental effects. Even the fundamental methods of measuring foam performance (knockdown, control, and extinguishment) vary. For example, Johnson[31] reported that FFFP fails the proposed ISO gentle application tests because small flames persist along a small area of the tray rim. He states that, to get around this inconvenience, the foam committees have redefined extinction to include flames. Given all of these variations, it is no wonder that tests and specifications for various foams and international standards have different requirements. This is reflected in table 18, which compares four key parameters of the MIL SPEC, UL, ICAO, and ISO standards. There is no uniform agreement between test fuel, application rate, the allowance to move the nozzle, and the extinguishment application density for AFFF. There is a factor

TABLE 15. SUMMARY OF HOSE REEL FIRE TEST DATA FROM SRDB[29]

Foam Type	Application	Test No.	90% Extinguishment Times (min : s)	100% Extinguishment Times (min : s)	Volume of Solution Used (gal (L))	Extinguishing Density (gal/ft^2 (L/m^2))	Burnback Time (min : s)
AFFF	Aspirated	3	1 : 08	1 : 45			8 : 43
		5	1 : 06	1 : 50			7 : 20
		9	1 : 24	2 : 26			5 : 42
		Average	1 : 13	2 : 00	200 (760)	0.12 (5)	7 : 15
AFFF	Nonaspirated (Spray)	6	2 : 42	4 : 39			2 : 00
		7	4 : 35	5 : 30			1 : 11
		8	3 : 25	4 : 22			2 : 17
		Average	3 : 34	4 : 50	450 (1700)	0.28 (11)	1 : 49
AFFF-AR	Aspirated	15	1 : 54	2 : 31			8 : 32
		16	0 : 57	1 : 25			6 : 48
		18	1 : 14	2 : 21			7 : 58
		Average	1 : 22	2 : 06	206 (780)	0.13 (5)	7 : 46
AFFF-AR	Nonaspirated (Spray)	19	4 : 26	5 : 27	527 (2000)	0.32 (13)	1 : 34
FFFP	Aspirated	4	1 : 07	2 : 18			13 : 40
		10	1 : 17	2 : 07			10 : 57
		11	1 : 23	2 : 01			6 : 46
		Average	1 : 16	2 : 09	209 (790)	0.13 (5)	10 : 28
FFFP	Nonaspirated (Spray)	12	3 : 54	4 : 26	426 (1600)	0.26 (11)	1 : 56
FFFP-AR	Aspirated	13	3 : 40	3 : 57			5 : 18
		14	1 : 56	3 : 50			10 : 22
		20	2 : 02	3 : 32			9 : 58
		Average	2 : 33	3 : 46	346 (1310)	0.21 (9)	8 : 33
FFFP-AR	Nonaspirated (Spray)	21	3 : 19	4 : 54	454 (1720)	0.28 (11)	4 : 07
FP	Aspirated (FRS Branchpipes)	29	1 : 39	3 : 15	315 (1200)	0.19 (8)	12 : 53
Halofoam	Nonaspirated (Spray)	22	3 : 46	5 : 52			4 : 40
		23	2 : 49	5 : 14			6 : 13
		Average	3 : 18	5 : 33	533 (2020)	0.37 (13)	5 : 27

TABLE 16. SUMMARY OF FIRE TEST DATA FROM FRDG[30]

Test	Foam Type and Normal Use Conc.	Conc. Used	Extinction Times (min : s)					Burnback Times (min : s)			
			90 %	95 %	Virtual Ext.	100 %	Foam App. Period	25 %	50 %	75 %	100 %
1	AFFF(1) 3%	3%	0 : 54	1 · 03	1 : 10	2 : 12	2 : 43	2 : 50	2 : 56	3 : 03	3 : 18
2	AFFF(1) 3%	3%	0 : 59	1 : 01	1 : 29	4 : 16	4 : 48	4 : 57	5 : 05	5 : 13	5 : 34
3	AFFF(1) 3%	2%	0 : 52	0 : 57	1 : 26	1 : 31	2 : 02	1 : 38	1 : 54	2 : 07	2 : 31
4	AFFF(2) 3%	3%	0 : 55	1 : 19	2 : 24	7 : 21	7 : 53	3 : 36	3 : 44	3 : 54	4 : 03
5	AFFF(2) 3%	2%	1 : 25	1 : 30	2 : 53	7 : 30	8 : 00	5 : 33	5 : 55	6 : 18	6 : 39
6	AFFF(1) 3%	1.5%	1 : 24	1 : 29	2 : 29	4 : 02	4 : 33	2 : 26	3 : 09	3 : 27	3 : 27
7	AFFF(2) 3%	1.5%	4 : 23	4 : 28	5 : 14	5 : 49	6 : 19	3 : 21	3 : 36	3 : 45	4 : 09
8	FFFP(1) 3%	3%	0 : 59	1 : 34	2 : 05	6 : 29	6 : 35	5 : 09	5 : 18	5 : 28	5 : 49
9	FFFP(1) 3%	2%	1 : 26	1 : 32	1 : 58	8 : 48	9 : 18	4 : 49	5 : 06	5 : 37	6 : 07
10	FFFP(2) 3%	3%	1 : 12	1 . 20	2 : 08	7 : 22	7 : 58	5 : 55	6 : 18	6 : 27	6 : 39
11	FFFP(2) 3%	2%	1 : 30	1 : 55	2 : 17	6 : 17	6 : 47	4 : 39	5 : 29	6 : 12	6 : 23
22	FFFP(1) 3%	3%	0 : 57	1 : 01	4 : 33	4 : 33	5 : 03	4 : 45	5 : 05	5 : 17	5 : 44
23	FFFP(2) 3%	3%	0: 53	0 : 57	1 : 37	4 : 21	4 : 51	6 :02	6 : 13	6 : 24	6 : 31
32	FFFP(1) 3%	1.5%	1 : 02	1 : 19	1 : 46	2 : 23	2 : 53	3 : 12	3 : 16	3 : 30	3 : 37
33	FFFP(2) 3%	1.5%	1 : 45	1 : 48	2 : 02	3 : 39	4 : 10	4 : 15	4 : 34	4 : 52	5 : 07
37	AFFF(2) 3%	3%	0 : 46	0 : 49	1 : 36	2 : 52	3 : 22	4 : 00	4 : 06	4 : 14	4 : 36
38	AFFF(1) 3%	3 %	0 : 45	0 : 49	1 : 29	3 : 55	4 : 25	6 : 15	6 : 25	6 : 51	7 : 04
43	AFFF(1) 3%	3 %	0 : 44	0 : 53	1 : 39	3 : 07	3 : 37	5 : 44	6 : 00	6 : 08	6 : 13

of six differences between the lowest permitted extinguishment application density (MIL SPEC) and the highest (ISO). This significant difference is attributed, at least in part, to the fixed nozzle requirement in the ISO specification.

TABLE 17. VARIABLES ASSOCIATED WITH FOAM PERFORMANCE AND TESTING

I. Physical/chemical properties of foam solution

A. Bubble stability

1. Measures

a. Expansion ratio
b. Drainage rate

2. Variables

a. Water temperature
b. Water hardness/salinity
c. Water contamination

B. Fluidity of foam

1. Measures

a. Viscosity
b. Spreading rate
c. Film formation

2. Variables

a. Fuel type and temperature
b. Foam bubble stability

C. Compatibility with auxiliary agents

1. Measures fire and burnback test
2. Variables

a. Other foam agents
b. Dry chemical agents

D. Effects of Aging

1. Measures fire and burnback test
2. Variable shelf life of agent

TABLE 17. VARIABLES ASSOCIATED WITH FOAM PERFORMANCE AND TESTING (continued)

II. Test methods to characterize foam performance

A. Fuel

1. Measures

a. Vapor pressure
b. Flash point
c. Surface tension
d. Temperature

2. Variables

a. Volatility
b. Depth and size
c. Initial temperature of air and fuel temperature
d. Time fuel has been burning (e.g., short versus long, and depth of hot layer)

B. Foam application method

1. Measures

a. Stream reach
b. Aspiration of foam
c. Foam stability, e.g., contamination by fuel
d. Water content of foam
e. Proportioning rate

2. Variables

a. Aspiration

(1) Effect on stream reach

(2) Degree to which foam is aspirated and the need to aspirate based on foam type

b. Fixed versus mobile device
c. Application technique

(1) Indirect, e.g., against backboard or sidewall
(2) Direct

TABLE 17. VARIABLES ASSOCIATED WITH FOAM PERFORMANCE AND TESTING (continued)

II. Test methods to characterize foam performance (continued)

(a) Gentle
(b) Forceful
(c) Subsurface injection

d. Application location

(1) High — need to penetrate plume
(2) Low

e. Application rate of foam

f. Wind (as it affects stream reach)

(1) Crosswind
(2) With and against

g. Effect of reduced or increased concentration due to improper proportioning

C. Fire configuration

1. Measures

a. Fuel burning rate, radiation feedback to fire
b. Propensity for reignition
c. Surface tension

2. Variables

a. Pan/containment geometry

b. Two-dimensional (pool) versus three-dimensional (running fuel/atomized spray)

c. Presence and temperature of freeboard

d. Wind (as it affects flame tilt and reradiation)

e. Surface on which there is fuel

(1) Rough
(2) Smooth
(3) Water substrate "peeling" effect of fuel

TABLE 17. VARIABLES ASSOCIATED WITH FOAM PERFORMANCE AND TESTING (continued)

II. Test methods to characterize foam performance (continued)

D. Measurement of Results

1. Measures

a. Time to knockdown, control, extinguish, and burnback

(1) Actual or estimated time by visual observations

(2) Summation values, i.e., summation of control at 10, 20, 30, and 40 seconds

b. Heat flux during extinguishment and burnback

2. Variables -- qualitative and quantitative methods to determine fire knockdown, extinguishment, and burnback

a. 90 percent control -- measure of ability of foam to quickly control the fire

b. 99 percent (virtual extinguishment) -- all but the last flame or edge extinguished

c. Extinguishment -- 100 percent

d. Burnback -- 25 percent, 50 percent

TABLE 18. EXAMPLES OF EXTINGUISHMENT APPLICATION DENSITIES OF VARIOUS TEST STANDARDS

Test Standard	Fuel	Application Rate (gpm/ft^2 (Lpm/m^2))	Nozzle Movement Permitted	Extinguishment Application Density (gal/ft^2 (L/m^2))
MIL SPEC	motor gasoline	0.04 (1.6)	yes	0.033 (1.34)
UL 162	heptane	0.04 (1.6)	yes	0.12 (4.9)
ICAO	kerosene	0.06 (2.5)	yes (horizontal plane)	0.061 (2.5)
ISO -- Forceful	heptane	0.06 (2.5)	no	0.19 (7.6)

No study has been performed to correlate these test methods; given the significant differences in performance characteristics and requirements, it is unlikely that correlation between these test methods could be established, even when considering AFFF only. An AFFF that meets the ICAO standard could not be said to meet the MIL SPEC without actual test data. The problem of correlating differences in small-scale tests was demonstrated by UL[32] in a comparison of UL, MIL SPEC, OF555 (U.S. Government protein spec) and United Kingdom test methods. In those tests, differences between different classes of agents (protein vs. AFFF) and between agents within a class (e.g., AFFF) were demonstrated. The results of the recent FRDG tests which indicate that all AFFF agents do not have similar performance characteristics confirm the previous UL findings.

The problem of correlation is compounded when a single test method is used in an attempt to assess different classes of foam, e.g., protein and AFFF. Attempts to use a single test method are problematic because of the inherent difference between these foams: protein foams require air aspiration so that the foam floats on the fuel surface. This stiff, "drier" foam is viscous and does not inherently spread well without outside forces (e.g., nozzle stream force). AFFF, because of its film formation characteristics, does not require the degree of aspiration that protein foams require. This heavier, "wetter" foam is inherently less viscous, which contributes to improved spreading and fluidity on fuel surfaces. This is related, at least in part, to the degree of aspiration of the foam. A more exact description of foam aspiration is appropriate. Thomas[33] has described three levels of foam aspiration: primary aspirated, secondary aspirated, and unaspirated. Primary aspirated foam occurs when a foam solution is applied by means of a special nozzle designed to mix air with the solution within the nozzle. The consequence is foam bubbles of general uniformity. "Air-aspirated" foam refers to this primary aspirated foam. Secondary aspirated foam results when a foam solution is applied using a nozzle which does not mix air with the solution within the nozzle. Air is, however, drawn into the solution inflight or at impact at the fire. Secondary aspirated foam refers to "nonair-aspirated" foam described in this report. Unaspirated foam occurs when a foam solution does not intake air to form foam bubbles at any stage. From a practical standpoint, unaspirated foam, even AFFF, is not effective on hydrocarbon fuel fires.

The correlation between foam solution viscosity and extinguishment time has been shown by Fiala[18], but the entire foam spreading and extinguishment theory has yet to be demonstrated based on first principles. Thus, the test standards adopt bench-scale tests which measure a factor of foam fluidity (e.g., spreading coefficient), but fail to recognize the total foam spreading system, including viscous effects. Fundamental understanding of foam mechanisms would promote the development of small/moderate-scale test apparatus which potentially have greater direct correlation for predicting large-scale results.

The NFPA committee charged with developing foam test criteria for the 1993 Edition of the NFPA 403 standard had to address both of these issues: the correlation between small-scale national and international standards with large-scale results, and the use of a single test method for all foams. The Aviation Committee had, for some time, recognized the need to provide guidelines or standards for foam agents. It had wrestled with the chemical and physical property differences between protein, fluoroprotein, and aqueous film-forming foams. The Aviation Committee established an Ad-hoc Task Group for Foam Test Performance Criteria. Initial suggestions by the members of the task group varied widely on the direction to pursue. Some recommended adoption or adoption in part of the MIL SPEC, UL 162, or ICAO methods while others suggested a single standard fire test with different application rates. The task group was directed by the Aviation Committee to examine ICAO test methods and philosophies. In particular, they were to examine the concept of using one fire test pan for all tests (i.e., all agents) and using different nozzles/flow rates for each required application density.

Preliminary tests using this approach were conducted under the direction of Underwriters Laboratories, Inc. Tests were conducted using the 50 ft^2 (4.6 m^2) ISO foam fire test pan. AFFF, FPF, and FP foams were tested using a 30-second, fixed nozzle application. At the end of 30 seconds, manual firefighting was permitted. The standard ISO DP 7203 burnback method was used. Initial testing with a 2 gpm (7.5 Lpm) application rate for AFFF and 3 gpm (11.4 Lpm) rate for PF and FPF were not sufficient to extinguish fires in 30 seconds. A 3 gpm (11.4 Lpm) rate for AFFF (0.06 gpm/ft^2) did not extinguish the fire within 60 seconds. Technique was found to be an issue with these tests. The NFPA Committee concluded the following:

1. Any standard or specification must address protein and fluoroprotein foams as well as film-forming foams. In particular, Europe and the United Kingdom use the protein-based foams for CFR. It is inappropriate to delete protein-based foams from the NFPA aviation standard even though the film-forming agents appear to offer more effective protection in terms of application rate requirements.

2. Likewise, it is not appropriate to reduce overall performance, particularly as it relates to AFFF, in an effort to reconcile all existing or potential international situations. For example, the ICAO extinguishment application density of 0.061 gal/ft^2 is 100 percent greater than that required in the MIL SPEC.

3. The development of a new test method is a lengthy, involved process which requires significant time and effort. In the near term, the development of a single test method which can be used to evaluate all foams is not particularly encouraging. It is improbable that a new method offers a near-term solution.

4. A codified method to judge foam performance is best accomplished by referencing existing test methods at this time.

5. The MIL SPEC for AFFF and UL 162 (Type 3 application) for protein and fluoroprotein foams provide near-term methods for establishing guidance/standards.

In a compromise, the Aviation Committee adopted the 50 ft^2 (4.6 m^2) MIL SPEC fire test method for AFFF and UL 162 method for protein and fluoroprotein foams. Any foam which is used at the lowest design application rate (0.13 gpm/ft^2 (5.5 Lpm/m^2)) must pass the MIL SPEC fire test. It was recognized that countries outside North America might want to adopt other standards, e.g., ICAO. The NFPA committee noted that it was incumbent on the authority having jurisdiction to assure that adopted methods are consistent with the minimum agent rate/quantities they have adopted.

Given the significant variables in test methods, one might conclude that the small-scale tests bear no relation to actual CFR situations. The next section demonstrates the correlation between the MIL SPEC fire test methods and large-scale CFR firefighting evolutions.

CORRELATION BETWEEN MIL SPEC FIRE TESTS AND LARGE-SCALE FIRES.

A comprehensive review of large-scale fire tests was performed as documented in Historical Basis and Test Results sections. In most of the tests cited, the AFFF used was on the MIL SPEC Qualified Products List or had been submitted for evaluation under the MIL SPEC. A key variable in the correlation was controlled: the AFFF agent, unless specifically noted, met the criteria of the MIL SPEC. Some protein foam data are also included.

Appendix C contains the complete set of fire test data. Variables in the assessment included the following:

1. The application rate — 0.03 - 0.36 gpm/ft^2 (1.2 - 14.8 L/m^2)
2. Test area — 28 ft^2 (2.6 m^2) to 16,000 ft^2 (1500 m^2)
3. Fuel — low and high flashpoint
4. Foam aeration — air-aspirating nozzle or nonair-aspirating nozzle

Ninety percent fire control times were used as the most accurate measure of the fire knockdown performances, which were reported in all tests. This recognizes the inherent ARFF philosophy that rapid knockdown of hydrocarbon fuel fires is required in aircraft incidents. The use of 90 percent control times also eliminates the variability of total extinguishment, which might be dependent on test bed edge effects or running fuel fire scenarios.

The effects of aspiration and fuels were investigated. While there are data which show that nonair-aspirated AFFF can be used to achieve more rapid control times (see Historical Basis section), there was no clear overall trend in the data in table C-1. For purposes of analysis, data for tests using aspirated or nonair-aspirated nozzles were combined. The effects of fuel differences are shown in figures 2 and 3. For purposes of this analysis, the low flashpoint fuels (less than 0°C), including gasoline, heptane, JP-4, Avgas, were used. Insufficient data were available to correlate small- and large-scale data with the higher flashpoint fuels. The tests compared used the manual application technique ("forceful" in ISO terms) where nozzle movement was permitted.

Application rate clearly has an effect on control and extinguishment times as demonstrated previously in figures 1 through 5. This was reconfirmed for the data as shown in figure 10, which includes data from all sizes of test fires. Control time increases exponentially as application rate decreases, particularly below 0.10 gpm/ft^2 (4.1 Lpm/m^2). Variability of the data is shown by the first standard deviation. This curve is somewhat flatter than the asymptomatic curves shown in the earlier work.

The scaling of small fires with large fires is shown in figures 11 and 12, which relate the time needed to control the burning fuel surface as a function of fire size. The time needed to control a unit of burning area (s/ft^2 or s/m^2), designated as the specific control time, is plotted as a function of fire size on logarithmical scales. For low (0.03 - 0.06 gpm/ft^2 (1.2 - 2.4 Lpm/m^2)) and intermediate (0.07 - 0.10 gpm/ft^2 (2.8 - 4.1 Lpm/m^2)) application rates, the specific control times decrease linearly as a function of fire area when plotted on log-log scales. Insufficient data were available to establish this correlation for higher application rates. These data are in agreement with data from Fiala[18], which also indicate decreasing specific extinguishment times as a function of burning area for increasing application rates of AFFF. Also, Fiala shows that, for a constant application rate, AFFFs have lower specific extinguishment times as a function of burning area than those of protein and fluoroprotein foams. Obviously, this linear relationship must change at very large areas; otherwise, the specific control/extinguishment time would go to zero. This is evidenced in figure 11, where the curve flattens at the high area end of the plot.

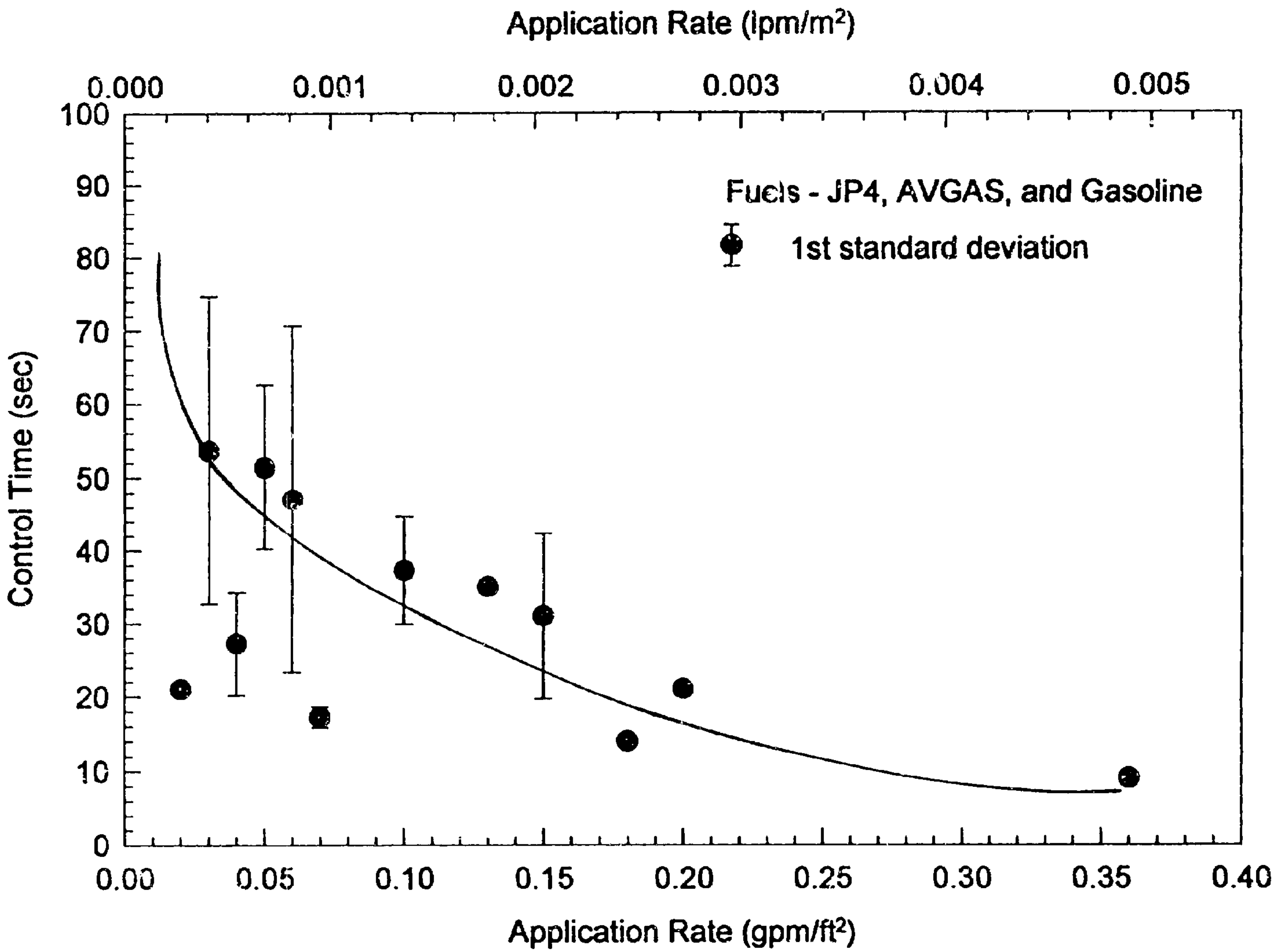

FIGURE 10. AFFF CONTROL TIME AS A FUNCTION OF APPLICATION RATE

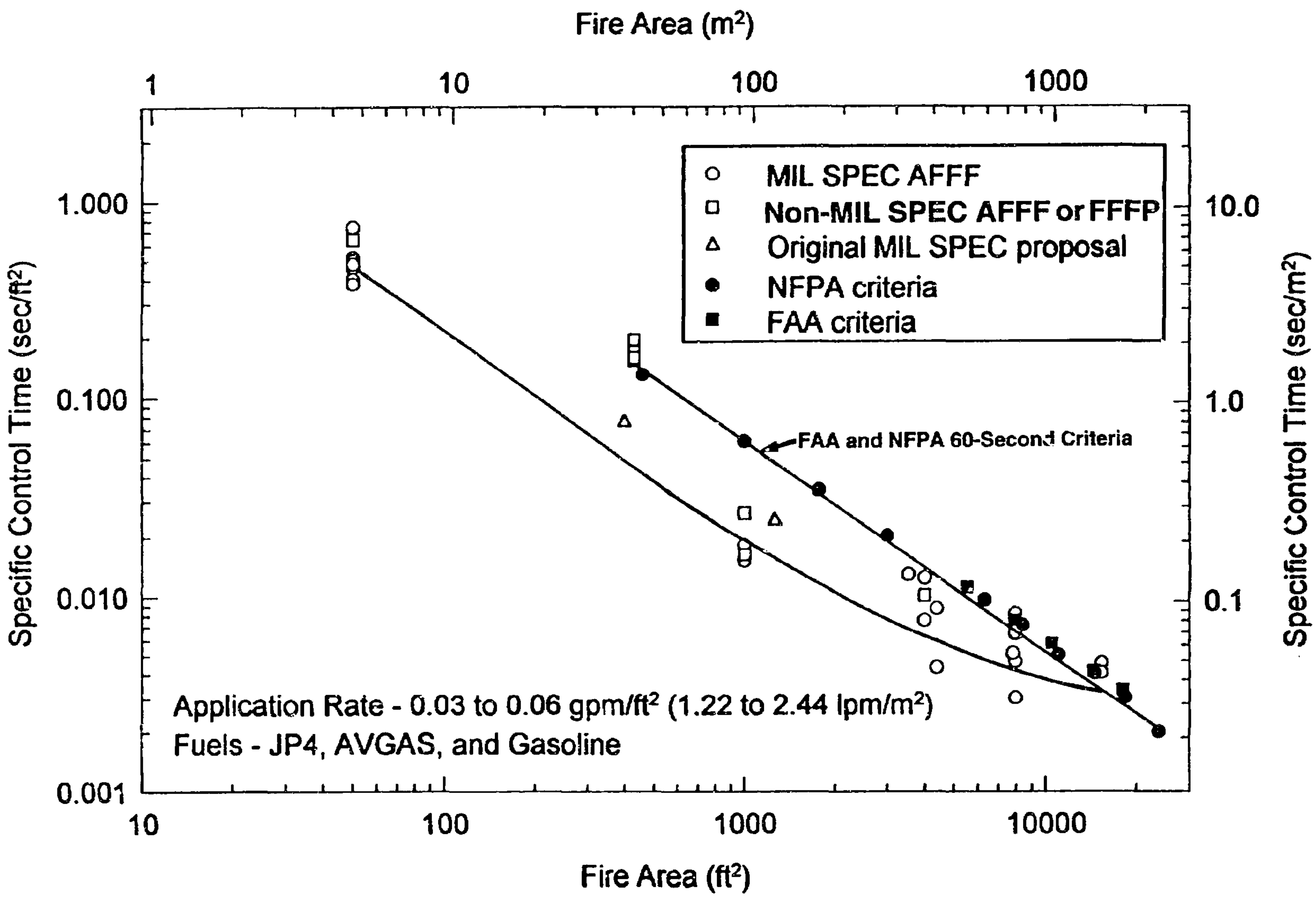

FIGURE 11. SPECIFIC CONTROL TIMES FOR AFFF AT LOW APPLICATION RATES

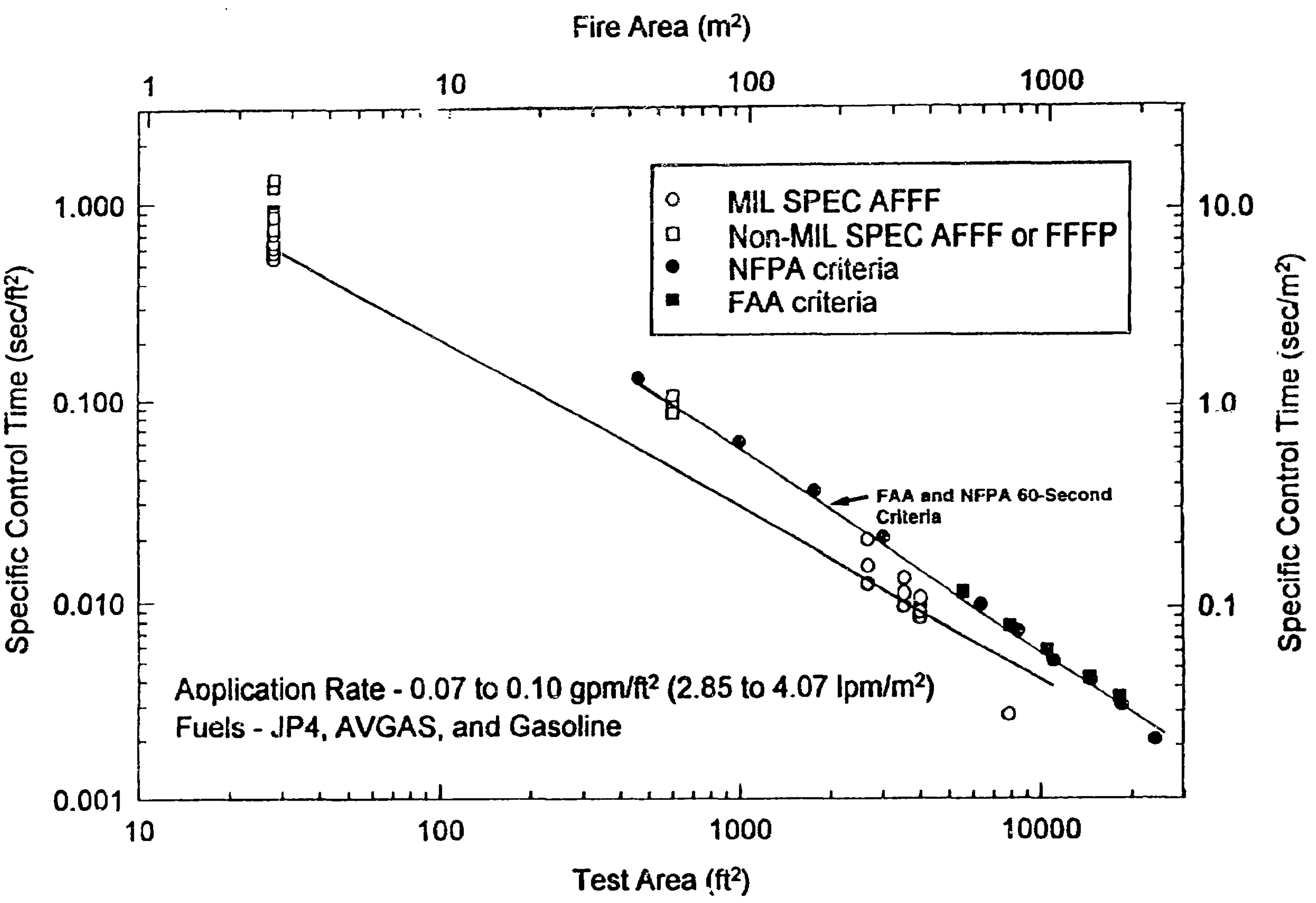

FIGURE 12. SPECIFIC CONTROL TIMES FOR AFFF AT INTERMEDIATE APPLICATION RATES

Figures 11 and 12 show that higher specific control times are required for the specification test fires (28 and 50 ft^2) compared to large fires. This is readily apparent as actual control times for the small fires are on the same order as results from large fires (table C-1). Figure 11 also shows specific control time criteria which was originally proposed for the MIL SPEC[12]. This original draft proposal included a requirement for 85 percent control in 30 seconds for a 400 ft^2 (37 m^2) and a 1200 ft^2 (110 m^2) fire. These requirements were considered redundant based on the small- and larger-scale developmental test data. They were deleted from the MIL SPEC requirements.

The FAA criteria for Index A-3 (NFPA 403 Category 1-10) airports is also shown in figures 11 and 12. Using the practical critical control area for these airports and the requirement for fire control in 60 seconds, specific control time as a function of area is shown. The data indicate that specific control times with MIL SPEC products applied at less than design application rates (i.e., 0.13 gpm/ft^2) can meet control times established by NFPA and FAA requirements. The limited data for AFFF and FFFP agents which do not meet MIL SPEC requirements suggest that these agents may not meet minimum NFPA and FAA required control times when applied at less than design rates.

From these data, it can be concluded that a scaling relationship exists between MIL SPEC small-scale fire tests and actual large-scale CFR scenarios. The MIL SPEC tests are more challenging than the larger tests in terms of time to achieve control, but this challenging test produces an agent that can meet NFPA and FAA requirements at less than the design application rate. The trend of the data suggests that non-MIL SPEC agent may not provide this same margin of safety.

ADDITIONAL PARAMETERS FOR FOAM SPECIFICATIONS

Fire control, extinguishment, and burnback performance are obviously the most important aspects of foam quality. There are other important aspects related to fire performance and overall foam quality. From a fire performance standpoint, AFFF of one particular vendor should be compatible with that of another. Both the NFPA and FAA caution against combining agents from different manufacturers without explicit guidance from the suppliers that this is acceptable. In practical terms, this restricts CFR users when they purchase new stocks of concentrate. Agents should also demonstrate compatibility with secondary extinguishing agents, e.g., PKP. It is desirable that a foam specification address these compatibility issues.

Researchers in the United Kingdom have identified a potential problem of agents proportioned at less than design concentration, e.g., 3 percent concentration proportioned at 1 or 2 percent (table 16). In this case, agents proportioned at less than the design concentration reportedly performed satisfactorily on small-scale tests, but at least one AFFF performed poorly in large-scale tests.

Other performance criteria are desirable from a quality control standpoint. These include proportioning, storage, and discharge characteristics (e.g., concentrate viscosity, pH, corrosivity), shelf life, and stability.

As described in table 9, the MIL SPEC includes criteria to address these foam parameters. In particular, there are compatibility and reduced concentrate strength tests to assure adequate performance under these conditions. For example, the fire performance of a MIL SPEC AFFF proportioned at half its design concentration is only permitted a 15-second increase in extinguishment time using the 28 ft^2 (2.6 m^2) test method. With this inherent safety factor designed into the agent, there is assurance that a misproportioned AFFF can still be used to combat a hydrocarbon pool fire. Interagent and PKP compatibility tests provide assurance that agents, if mixed or used with PKP, will not degrade in performance. Chemical and physical characteristics tests are required in the MIL SPEC to assure overall quality control. Taken overall, the requirements of the MIL SPEC have resulted in the procurement of agents with superior fire performance, proportioning, storage, and shelf life characteristics. These requirements have been developed and refined over more than 25 years of field use in military aviation and shipboard use.

An issue for FAA certification is the need to enforce or enact the entire MIL SPEC or specific criteria related to fire performance, burnback performance, film formation and sealability, and PKP compatibility. In particular, salt water and packaging requirements may not be critical to assure adequate foam performance at FAA certified airports. Some of the packaging requirements involve military logistical requirements and have no obvious civilian application other than providing adequate container integrity and identifying MIL SPEC agents by packaging color code. Salt water test requirements may be applicable if there are situations where brackish water might be used for proportioning foam.

An issue is whether foam concentrates would be reformulated by suppliers if selected performance criteria are specified, e.g., 50 ft^2 fire and burnback test, PKP compatibility, and film formation only required. Informal discussions with vendors indicate that current MIL SPEC agents may indeed be reformulated if performance requirements are relaxed. For example, formulations which require less fluorosurfactants may be developed if the half strength test is deleted. Cost savings from reduced fluorosurfactant content provide vendors with the impetus to develop such a product. The correlations developed over years of experience (e.g., appendix C) may not apply to these formulations. The scaling relationships (figures 10 and 11), factor of safety, and overall confidence in the agent would have to be reestablished. This would have to be accomplished through a large-scale research project.

Given the implications of reestablishing the baseline performance, it appears reasonable to maintain the MIL SPEC in its entirety if it is adopted for FAA certification purposes.

CONCLUSIONS

1. FAA primary foam agent requirements are based on rapid control and extinguishment of a hydrocarbon fuel fire.

2. Large-scale testing was performed to establish minimum AFFF application rates and quantities. These rates and quantities, the lowest permitted for all foam agents, were based on tests with AFFF agents from the MIL SPEC QPL, or agents in substantial conformance with QPL products.

3. There are a wide range of methods and requirements between standard test methods. Differences are substantial even when comparing fundamental measures of foam performance, e.g., extinguishment application density. The MIL SPEC has the most stringent requirements of the standards and specifications reviewed.

4. Fire control results from small-scale MIL SPEC AFFF tests correlate with large-scale test data.

5. Based on the small- to large-scale correlation, agents which meet the MIL SPEC can meet FAA and NFPA criteria at application rates less than the design application rates of 0.13 gpm/ft^2 (5.5 Lpm/m^2). This provides a factor of safety for products used at the lowest foam agent application

rate. The limited data available suggest agents that fail to meet the MIL SPEC criteria may not provide this same factor of safety.

6. Given the critical times involved in survivable postcrash fires and the probability that quantities of agent required to extinguish actual aircraft fires may be greater than those for test fires, the factor of safety inherent in MIL SPEC agents is entirely appropriate for FAA certification purposes. The safety factor is needed to address factors such as the level of training of firefighting personnel, inaccessibility of shielded fires, initial overuse of foam, three-dimensional fire scenarios, and difficulties in deployment and control.

7. While MIL SPEC AFFF has been shown to be a superior firefighting agent, no correlation has been established between small-scale physical/chemical properties tests and actual fire and burnback performance.

8. Many of the performance criteria in the MIL SPEC are relevant to civilian aviation situations, e.g., interagent compatibility, PKP compatibility, and performance of misproportioned and old agents.

9. Modifications in the adoption of MIL SPEC criteria may result in formulations which impact overall foam quality. This may require reestablishment of the correlation demonstrated between the small- and large-scale test results.

10. The proliferation of standard test methods and criteria has not yielded significant benefits in our understanding of fundamental foam extinguishing mechanisms. Future work should focus on the use of first principles to establish fundamental foam extinguishment mechanisms.

RECOMMENDATIONS

1. The FAA should adopt the MIL SPEC in its entirety as criteria for accepting foam agents used at the 0.13 gpm/ft^2 (5.5 Lpm/m^2) application rate ("AFFF" flow rate category).

2. Conformance with the UL 162 standard is acceptable for agents used at the higher 0.20 gpm/ft^2 (8.2 Lpm/m^2) application rate.

3. The FAA should support research and development of bench-scale test methods based on first principles, which can be used to predict large-scale performance. Optimally, these methods could be used to predict performance of any foam agent on a hydrocarbon fuel spill fire. They could also be used to evaluate alternative foam agent formulations at a bench scale.

REFERENCES

1. Federal Aviation Administration, "Aircraft Fire and Rescue Facilities and Extinguishing Agents," Advisory Circular No. 150/5210-65, Washington, DC, January 28, 1985.

2. Geyer, G., "Equivalency Evaluation of Firefighting Agents and Minimum Requirements at U.S. Air Force Airfields," FAA Technical Report DOT/FAA/CT-82/109, Atlantic City, NJ, October 1982.

3. National Fire Protection Association, "NFPA 403, Standard for Aircraft Rescue and Firefighting Services at Airports," Quincy, MA, 1993 Edition.

4. Underwriters Laboratories, Inc., "UL 162, Standard for Foam Equipment and Liquid Concentrates," Northbrook, IL, Sixth Edition, March 7, 1989.

5. Lindemann, T., "Aircraft Fire Fighting -- In Three Minutes or Less," *Industrial Fire World*, **5** (1), February/March 1990, pp. 16-24.

6. Geyer, G.B., "Effect of Ground Crash Fire on Aircraft Fuselage Integrity," FAA Report RD-69-46, Atlantic City, NJ, December 1969.

7. Geyer, G.B., "Evaluation of Aircraft Ground Firefighting Agents and Techniques," Tri-Service System Program Office for Aircraft Ground Fire Suppression and Rescue, Technical Report AGFSRS 71-1, Wright-Patterson AFB, OH, February 1972.

8. Eklund, T.I., and Sarkos, C.P., "The Thermal Impact of External Pool Fires on Aircraft Fuselages," *Journal of Fire and Flammability*, **11**, July 1980, p. 231.

9. International Civil Aviation Organization, "Rescue and Fire Fighting Panel, Second Meeting, Montreal, 5-16 June 1972 Report," ICAO, Montreal, Quebec, Canada, 1972.

10. Federal Specification, "O-F-555b, Foam-forming Liquids, Concentrated Fire Extinguishing, Mechanical," March 11, 1964.

11. Military Specification, "Fire Extinguishing Agent, Aqueous Film-forming Foam (AFFF) Liquid Concentrate, Six Percent for Fresh and Seawater," MIL-F-24385 (Navy), November 21, 1969, superseding MIL-F-23905B.

12. Darwin, R.L., and Jablonski, E.J., "Full-scale Fire Test Studies of Seawater Compatible 'Light Water' as Related to Shipboard Fire Protection," Department of Navy Report, Washington, DC, August 25, 1969.

13. Military Specification, "Fire Extinguishing Agent, Aqueous Film-forming Foam (AFFF) Liquid Concentrate, for Fresh and Seawater," MIL-F-24385F, 7 January 1992.

14. Geyer, G.B., "Firefighting Effectiveness of Aqueous Film-forming Foam (AFFF) Agents," FAA Technical Report FAA-NA-72-48, prepared for the DOD Aircraft Ground Fire Suppression and Rescue Unit (ASD-TR-73-13), Washington, DC, April 1973.

15. Geyer, G.B., Neri, L.M., and Urban, C.H., "Comparative Evaluation of Firefighting Foam Agents," FAA Technical Report FAA-NA-79-2, Washington, DC, August 1979.

16. Jablonski, E.J., "Comparative Nozzle Study for Applying Aqueous Film-forming Foam on Large-scale Fires," U.S. Air Force Report, CEEDO-TR-78-22, April 1978.

17. Miller, T.E., "Evaluation of Film-forming Fluoroprotein Foam," Mobil Research and Development Corporation Technical Report (unpublished).

18. Fiala, R., "Aircraft Postcrash Firefighting/Rescue," from AGARD Aircraft Fire Safety Lecture Series No. 123, June 1982.

19. Aubert, J.H., Kraynik, A.M., and Rand, P.B., "Aqueous Foams," *Scientific America*, **19** (1), 1988, pp. 74-82.

20. Franeen, V.L., "Fire Extinguishing Composition Comprising a Fluoroaliphatic and a Fluorine Free Surfactant," U.S. Patent 3,562,156, 1971.

21. Rosen, M.J., *Surfactants and Interfacial Phenomena*, John Wiley and Sons, NY, 1989, Chapters 1, 5 and 7.

22. Tuve, R.L., Peterson, H.B., Jablonski, E.J., and Neill, R.R., "A New Vapor-securing Agent for Flammable Liquid Fire Extinguishment," NRL Report 6057, March 1964.

23. Underwriters Laboratories Inc., *Fire Protection Equipment Directory*, 1993 Edition, Northbrook, IL.

24. Scheffey, J.L., Darwin, R.L., Leonard, J.T., Fulper, C.R., Ouellette, R.J., and Siegmann, C.W., "A Comparative Analysis of Film Forming Fluoroprotein Foam (FFFP) and Aqueous Film Forming Foam (AFFF) for Aircraft Rescue and Fire Fighting Services," Hughes Associates, Inc. Report 2108-A01-90 for the NFPA Aviation Committee, June 1990.

25. International Organization for Standardization, "Fire Extinguishing Media Foam Concentrates Part 1: Specification for Low Expansion Foam Characteristics for Top Application to Water Immiscible Liquids," ISO Draft Standard, ISO/DIS 7203-1, 1992.

26. Underwriters Laboratories, Inc., "Proposed Requirements for the Sixth Edition of the Standard for Foam Equipment and Liquid Concentrates," *Report of Industry Advisory Conference*, Northbrook, IL, September 1992.

27. U.S. Department of Defense, "Qualified Products List of Products Qualified Under Military Specification MIL-F-24385 Fire Extinguishing Agent, Aqueous Film Forming Foam (AFFF) Liquid Concentrate, for Fresh and Sea Water," QPL-25385-25, Washington, DC, 21 May 1992.

28. Geyer, G.B., "Status Report on Current Foam Firefighting Agents," presented at the International Conference on Aviation Fire Protection, Interlaken, Switzerland, 22-24 September 1987.

29. Foster, J.A., "Additions for Hosereel Systems: Trials of Foam on 40 m^2 Petrol Fires," Home Office Scientific Research and Development Branch Report 40/87, London, 1987.

30. Johnson, B.P., "A Comparison of Various Foams When Used Against Large-scale Petroleum Fires," Home Office Fire Research and Development Office, Pub. 2/93, 1993.

31. Foster, J.A., and Johnson, B.P., "The Use of Fire Fighting Foam in the UK Fire Service," *First International Conference on Fire Suppression Research Proceedings*, Stockholm and Boras, Sweden, Swedish Fire Research Board, Stockholm and National Institute of Standards and Technology, Gaithersburg, MD, May 5-8-93, pp. 291-299.

32. Carey, W.M., and Suchomel, M.R., "Testing of Fire Fighting Foam," Underwriters Laboratories Report No. CG-M-1-81, Northbrook, IL, November 1980.

33. Thomas, M.D., "UK Home Office Research into Domestic Fire Fighting," *First International Conference on Fire Suppression Research Proceedings*, Stockholm and Boras, Sweden, Swedish Fire Research Board, Stockholm and National Institute of Standards and Technology, Gaithersburg, MD, May 5-8-93, pp. 283-289.

Appendix A

Comparison of the Physical and Chemical Properties
of Protein-based and Aqueous Film-forming Foams

BACKGROUND

Attempts have been made to classify foam firefighting agents strictly on their physicochemical properties. This section documents testing of fundamental foam properties and compares results with standard fire tests. Except where noted, all tests were conducted in accordance with Revision C of the MIL SPEC, MIL-F-24385C.

Variables of foam agents which could influence fire extinguishment and burnback performance include the following:

a. Physical/chemical properties of foam solution

   (1) Foam bubble stability: Expansion and drainage

      (a) Water temperature
      (b) Water hardness
      (c) Water contamination, e.g., salt water

   (2) Fluidity

      (a) Viscosity of foam solution
      (b) Ability to form a film - spreading coefficient

         (i) Fuel type
         (ii) Fuel temperature

b. Test methods/extinguishment

   (1) Application method

      (a) Fixed v. movable nozzle

      (b) Aspirating v. nonair-aspirating nozzle

         (i) Stream reach and pushing effect of hose stream
         (ii) Need to aspirate based on foam

      (c) Direct vs. indirect

         (i) Gentle
         (ii) Plunging
         (iii) Against-the-backboard

(2) Fuel

(a) Type

(i) Vapor pressure
(ii) Flashpoint
(iii) Surface tension

(b) Temperature

(i) Initial
(ii) Preburn time

(3) Fire size -- burning rate (effects of variable burning rate at less than 1 m diameter)
(4) Pan configuration

(a) Geometry (square vs. round)
(b) Freeboard (hot edge effect)

c. Environment

(1) Wind

(a) Flux to fuel surface
(b) Effects on foam stream reach

(2) Substrate

(a) Smooth vs. rough
(b) "Peeling" on water substrate

The work described in this appendix is based on work performed by George Geyer of the FAA based on data presented at the International Conference on Aviation Fire Protection in Interlaken, Switzerland, 1987. The data were developed in an attempt to distinguish test methods and criteria for protein-based and film-forming foams.

DISCUSSION

The firefighting effectiveness of the foam produced by the perfluorinated surfactants is enhanced by the aqueous fluorocarbon film, which floats on the surface of hydrocarbon fuels as it drains from the foam blanket. The mechanism whereby the fluorocarbon surfactants function as effective vapor securing agents is based upon their effect in reducing the surface tension of water and of their controllable oleophobic and hydrophilic properties. These properties provide a means for controlling the physical properties of water, enabling it to float and spread across the surface of a hydrocarbon fuel even though it is more dense than the substrate. This unique property led to the term "light water," which appeared in several of the early military specifications defining the properties of this class of agents.

According to classical theory[A1] concerning the spreading of insoluble films on liquid surfaces, the following equation maintains

$$SC = o - (w + i) \tag{A1}$$

where	SC	=	spreading coefficient of the aqueous fluorocarbon solution,
	o	=	surface tension of the fuel,
	w	=	surface tension of the aqueous film, and
	i	=	interfacial tension between fuel and the aqueous film.

If the spreading coefficient has a value greater than zero (i.e., positive), the aqueous phase can spread spontaneously upon or "wet" the fuel. A coefficient below zero (i.e., negative) indicates that it cannot spread spontaneously. When the spreading coefficient is zero, the two liquids are miscible.

Although this equation is applicable to pure liquids, there is wide variation possible when aqueous fluorocarbon films spread on a hydrocarbon fuel because of the variable oleophobic and hydrophobic properties of the fluorocarbon moieties. It is, therefore, appropriate to assess the interrelationship between firefighting effectiveness and the surface activity of the aqueous films produced by AFFF agents.

The physical modifications of protein hydrolyzates, which may be accomplished by the addition of fluorocarbon surfactants, is summarized in figure 6 in the main text. In this diagram, fluoroprotein foams and aqueous film-forming fluoroprotein foams are indicated as lying in a variable position between protein foam on the left and aqueous film-forming foam on the right. If small quantities of suitable fluorocarbon surfactants are added to protein hydrolyzates, the resulting product may produce foam, which demonstrates good stability toward dry chemical powder, with improved oleophobicity and greater burnback resistance to aircraft fuels. If larger quantities of suitable fluorocarbons are incorporated into the basic protein hydrolyzate, the surface tension of the solution, which drains from the foam, may be lowered to a value which permits it to spread spontaneously across the surface of liquid hydrocarbon fuels. Under these conditions, the generic term, "fluoroprotein foam," would still apply, but the physical properties of the foam would approach or equal those of the aqueous film-forming foams. Foam liquid concentrates of this type are classified as film-forming fluoroprotein foams.

PHYSICAL AND CHEMICAL PROPERTIES OF FOAM AGENTS.

The chemical composition of 24 agents evaluated under this project is presented in tables A-1 and A-2. Table A-1 provides the composition of the purely synthetic aqueous film-forming foams while table A-2 presents the composition of those concentrates which are comprised either wholly or partially of a protein hydrolyzate.

Tests to identify these properties were conducted in accordance with the MIL SPEC. The importance of these properties is described in table 9 of the main text. For example, chloride content is intended to be an indicator of corrosion potential to proportioning system pumps and equipment. Fluorine content is used in the MIL SPEC as a quality control indicator for each qualified agent. Refractive index is used as a method to determining proportioning accurately.

CORROSIVITY OF FOAM AGENTS.

There has recently been concern related to the corrosivity of foam agents when discharged on metal (aircraft) surfaces. The total quantity of halide permitted in the Type 3 percent and Type 6 percent aqueous film-forming foams in the MIL SPEC are 500 parts per million (ppm) and 250 ppm, respectively, when tested in accordance with ASTM D1821. However, other foam agents not manufactured in accordance with the military specification were found to contain very large quantities of halide salts. As a result, tests were conducted to determine the corrosive rate of seven foam firefighting agents against three common construction materials: cold rolled low carbon steel (UNS G101100), aluminum (1061), and stainless steel (304). The maximum permissible corrosion rate of a foam liquid concentrate exposed to steel (UNS G10100) under MIL-F-24385C is 1.6 milli-inches/year, but there are no maximum rates specified for aluminum or stainless steel.

The results of the corrosion tests with seven foam agents and three construction metals are summarized in table A-3 and plotted in figure A-1. The metal corrosion rates are the averages of five individual tests performed with each foam liquid and metal combination.

The corrosive rate on the cold rolled steel coupons produced by the seven foam agents is plotted in figure A-1 along with their respective halide concentrations. An analysis of these data shows that the halide content of the synthetic-type AFFF agents is relatively low (i.e., from 13.9 to 1,285 mg/L) and that the corrosive rate is not proportional to the halide content. This result was unexpected and may involve the common ion effect in suppressing corrosion of the metal. However, the corrosion rate of the steel coupons was not proportional to the halide content (i.e., from 12,589 to 65,281 mg/L) of those foam agents which contain protein.

Although the halide content of the seven foam agents varied widely (i.e., from 13.9 to 65,281 mg/L), none exceeded the maximum allowable corrosion rate of 1.5 milli-inches/year specified in MIL-F-24385C for steel.

TABLE A-1. PHYSIOCHEMICAL PROPERTIES OF AFFF CONCENTRATES

Concentrate	Type of Foam	Chloride Content (mg/L)	Density @ 25°C (g/mL)	Fluorine Content % by Wt.	pH	Refractive Index @25°C	Solid Content % by Wt.
3M Company							
Light water FC 206 CE 6%	AFFF-MIL	11.7	1.025	1.03	8.52	1.3612	4.3
Light water FC 203 CE 3%	AFFF-MIL	31.5	1.026	2.02	7.62	1.3774	6.5
Light water FC 201 CE 1%	AFFF	109.0	1.097	8.42	8.32	1.3975	22.5
Light water FC 600 3%/6%	AFFF-AR		1.023	1.34	7.67	1.3545	6.5
Angus Fire Armour							
Tridol 6%	AFFF	257.0	1.010	0.538	7.38	1.3461	3.5
Tridol 3%	AFFF	1285.0	1.042	0.650	7.71	1.3656	10.69
Ansul Fire Protection							
Ansulite AFC3 6%	AFFF-MIL	13.9	1.007	0.487	7.31	1.3616	1.75
Ansulite AFC3A 3%	AFFF-MIL	13.9	1.014	0.799	7.18	1.3657	3.92
Ansulite 1%	AFFF	15.3	1.029	2.62	7.21	1.3894	10.50
Ansulite ARC 3%/6%	AFFF-AR		1.003	0.358	7.91	1.3589	3.84
National Foam Systems, Inc.							
Aer-O-Water 6%	AFFF	236.0	1.010	0.549	7.44	1.3468	3.29
Aer-O-Water 3%	AFFF	422.0	1.049	0.664	8.02	1.3674	15.03
Aer-O-Water 3% Military 3%	AFFF-MIL	411.0	1.075	1.649	7.70	1.3586	19.73
Universal 3%/6%	AFFF-AR	1542.0	1.013	0.567	7.63	1.3503	7.01

TABLE A-2. PHYSIOCHEMICAL PROPERTIES OF PROTEIN CONTAINING CONCENTRATES

Concentrate	Type of Foam	Chloride Content (mg/L)	Density @ 25°C (g/mL)	Fluorine Content % by Wt.	pH	Refractive Index @25°C	Solid Content % by Wt.
Angus Fire Armour							
Petroseal 6%	FFFP	54,178	1.151	0.273	6.94	1.3998	31.97
Petroseal 3%	FFFP	65,281	1.170	0.361	6.88	1.4180	38.15
Alcoseal 3%/6%	FFFP-AR	2,827	1.081	0.387	6.49	1.3909	26.82
FP 570 6%	FPF	47,702	1.125	0.041	7.47	1.3925	27.97
FP 70 3%	FPF	37,527	1.148	0.068	7.19	1.4011	32.39
Nicerol 6%	PF	41,944	1.108	0.007	6.93	1.3866	24.67
Nicerol 3%	PF	62,197	1.149	0.003	6.48	1.4041	35.63
National Foam Systems, Inc.							
Aer-O-Film 3%	FFFP	2,210	1.146	0.495	7.75	1.3686	15.20
XL-6	FPF	12,748	1.128	0.075	7.09	1.4141	33.98
XL-3	FPF	21,589	1.131	0.091	6.97	1.4292	41.96

TABLE A-3. SUMMARY OF CORROSION TESTS

Foam Agents	3M FC 203 CE	Angus Tridol 3%	Ansul AFC-3A	National Foam AFFF 3%	Angus Petroseal 3%	Angus FP 70	National Foam XL3
Halide Content (mg/L)	31.5	1,285	13.9	422	65,281	37,527	21.589
Steel (G10100) (mg) Weight loss (-) Weight gain (+)	-49.47	7.56	−78.06	−36.66	−51.95	−110.67	−57.39
Corrosion milli-inches/year maximum 1.5	0.644	0.098	1.02	0.478	0.68	1.446	0.772
Aluminum (6061) Weight loss (-) Weight gain (+)	3.92	-2.27	-0.246	+0.11	-1.172	−3.86	0.938
Corrosion milli-inches/year	None measurable	0.107	None measurable	0.0006	0.08	0.154	0.036
Stainless Steel (304) Weight loss (-) Weight gain (+)	5.57	0.076	0.01	−0.252	−0.264	−0.364	−0.366
Corrosion milli-inches/year	None measurable	0.00006	0.0003	0.0032	0.0034	0.0048	0.0048

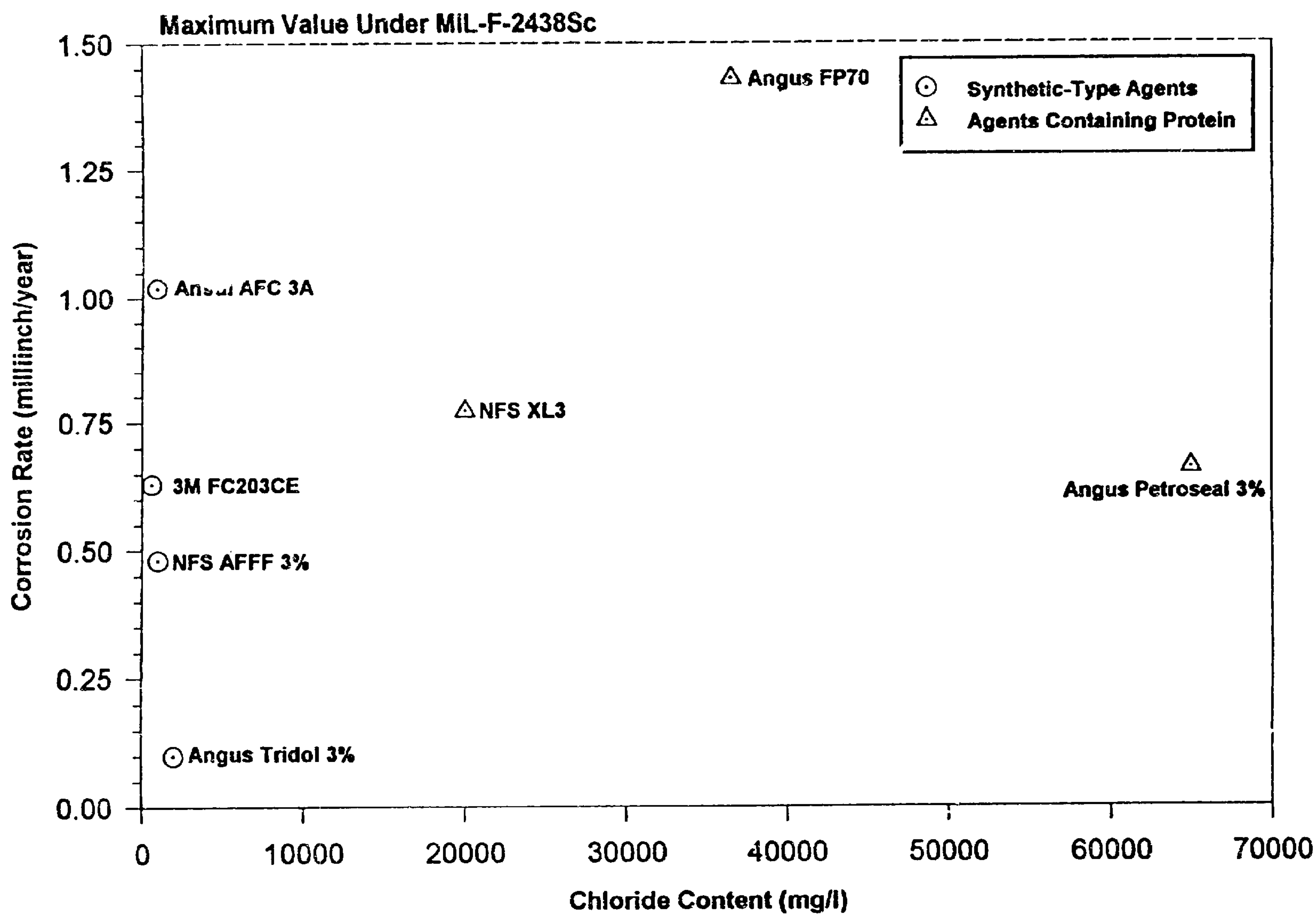

FIGURE A-1. CORROSION RATE OF FOAM FIREFIGHTING AGENTS AGAINST STEEL (UNS G10100) VS. THEIR CHLORIDE CONTENT

RELATIONSHIPS BETWEEN SPREADING COEFFICIENT, FLUORINE CONTENT, AND FIRE PERFORMANCE.

Film-forming foams produce a stable aqueous fluorocarbon film on the surface of hydrocarbon fuels. The ability to form a film, as indicated by a positive spreading coefficient, is dependent on the foam agent, the test fuel, and the fuel temperature. Baseline data for spreading coefficients, based on the MIL SPEC test criteria (ASTM D1331) with cyclohexane as the test fuel, is shown in tables 10 and 11 of the main report. Protein foams do not form a film and have a negative spreading coefficient. For example, Angus Nicerol 3%, a protein foam, has a spreading coefficient of 30.63. Angus FP 70 3% and National XL3 3%, both fluoroprotein foams, have spreading coefficients of -12.69 and -12.44, respectively, on cyclohexane. These foams must be highly expanded so that they float on the fuel surface, i.e., have a density less than the fuel. As noted in the main report, there is no 1:1 correlation between spreading coefficient and fire extinguishment and burnback time when cyclohexane is used as the test fuel.

EFFECTS OF TEST FUEL ON SPREADING COEFFICIENT.

Experiments were conducted to determine the effect of differences in the values of the spreading coefficient using various test fuel types. Six aqueous film-forming foam agents, none of which were MIL SPEC products, were used in the comparison.

The profiles presented in figure A-2 show the spreading coefficient for the six different aqueous film-forming foams when tested against n-heptane, cyclohexane, and Avgas.

The surface tension of the test fuels show that n-heptane (19.11 dynes/cm) and Avgas (19.20 dynes/cm) have almost identical values while that for cyclohexane (22.75 dynes/cm) is significantly higher. The spreading coefficient data for six AFFF agents with cyclohexane indicate that four agents (Angus Alcoseal, 3M FC600, Angus Petroseal, and 3M FC201) failed to meet the minimum requirement of +3 under MIL-F-24385C while two agents (National Aer-O-Film, and Angus Tridol 3%) exceeded the minimum requirement. The spreading coefficient of the same agents evaluated against n-heptane and Avgas showed that only two had positive values (National Aer-O-Film and Angus Tridol) while the remaining four (Angus Alcoseal, Angus Petroseal, 3M FC 600, and 3M FC 201) had negative spreading coefficient values.

Each of the six aqueous film-forming foam agents was tested for fire performance employing the 50 ft^2 (4.6 m^2) fire test procedure under MIL-F-24385C using n-heptane, Avgas, and motor gasoline as the test fuels. The maximum fire extinguishing time for this procedure, using motor gasoline (VV-G-1690) is 50 seconds using the standard 2 gpm (7.6 Lpm) nozzle.

The data shown, in figure A-3, shows that there is no direct correlation between the value of the spreading coefficient and the time to extinguish the n-heptane and Avgas fires using Angus Alcoseal, Angus Petroseal, 3M FC 600, and National Aer-O-Film. Although Angus Alcoseal and Angus Petroseal both have negative spreading coefficients with these fuels, they were able to extinguish the n-heptane and Avgas fires within 50 to 70 seconds. The 3M FC 600 agent, which also has a negative spreading coefficient with these fuels, extinguished these fires in less than 40 seconds. However, National Aer-O-Film, which has a small positive spreading coefficient with n-heptane and Avgas, required between 60 and 70 seconds for extinguishment.

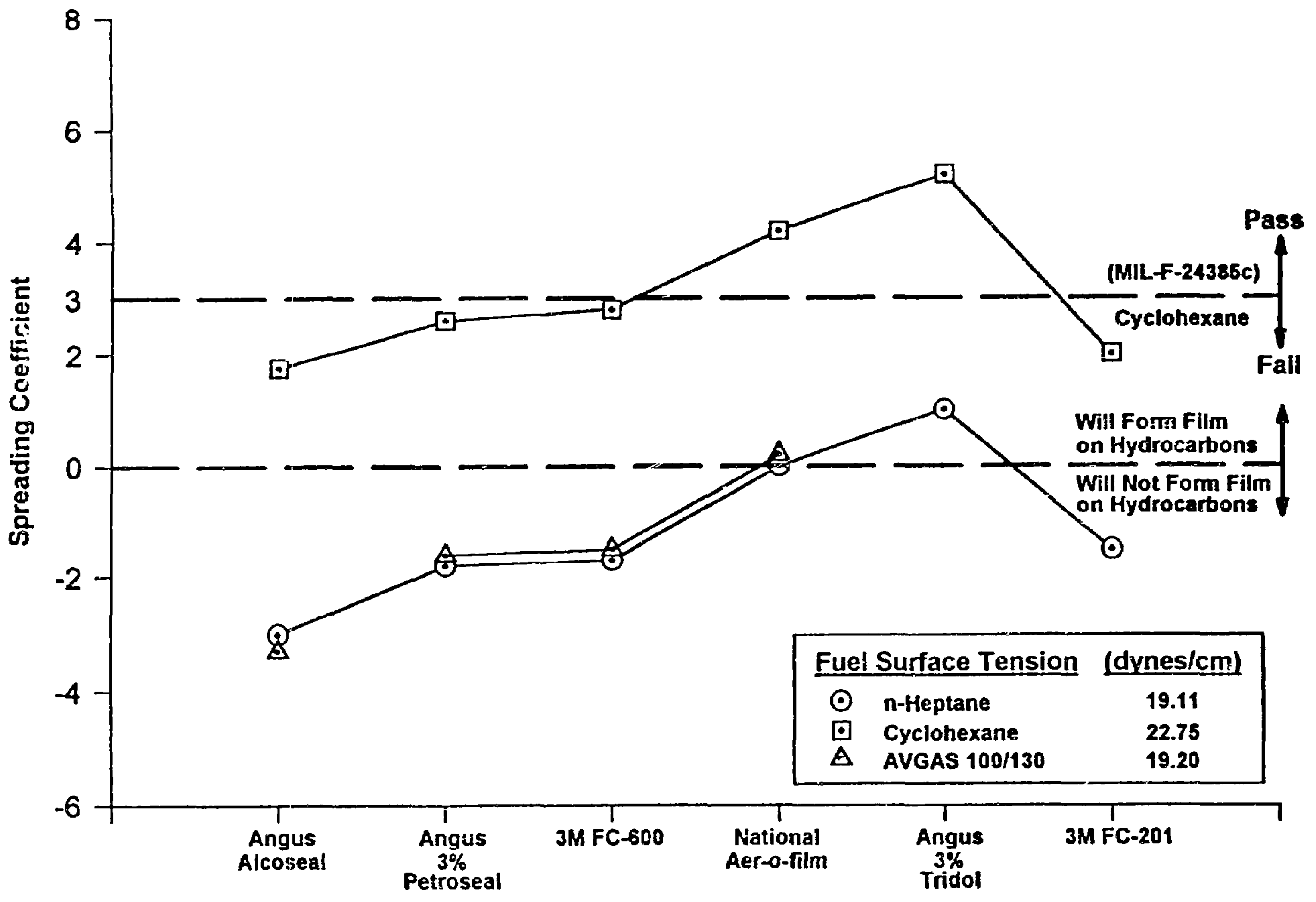

FIGURE A-2. SPREADING COEFFICIENTS FOR FILM-FORMING FOAM AGENTS ON THREE TEST FUELS

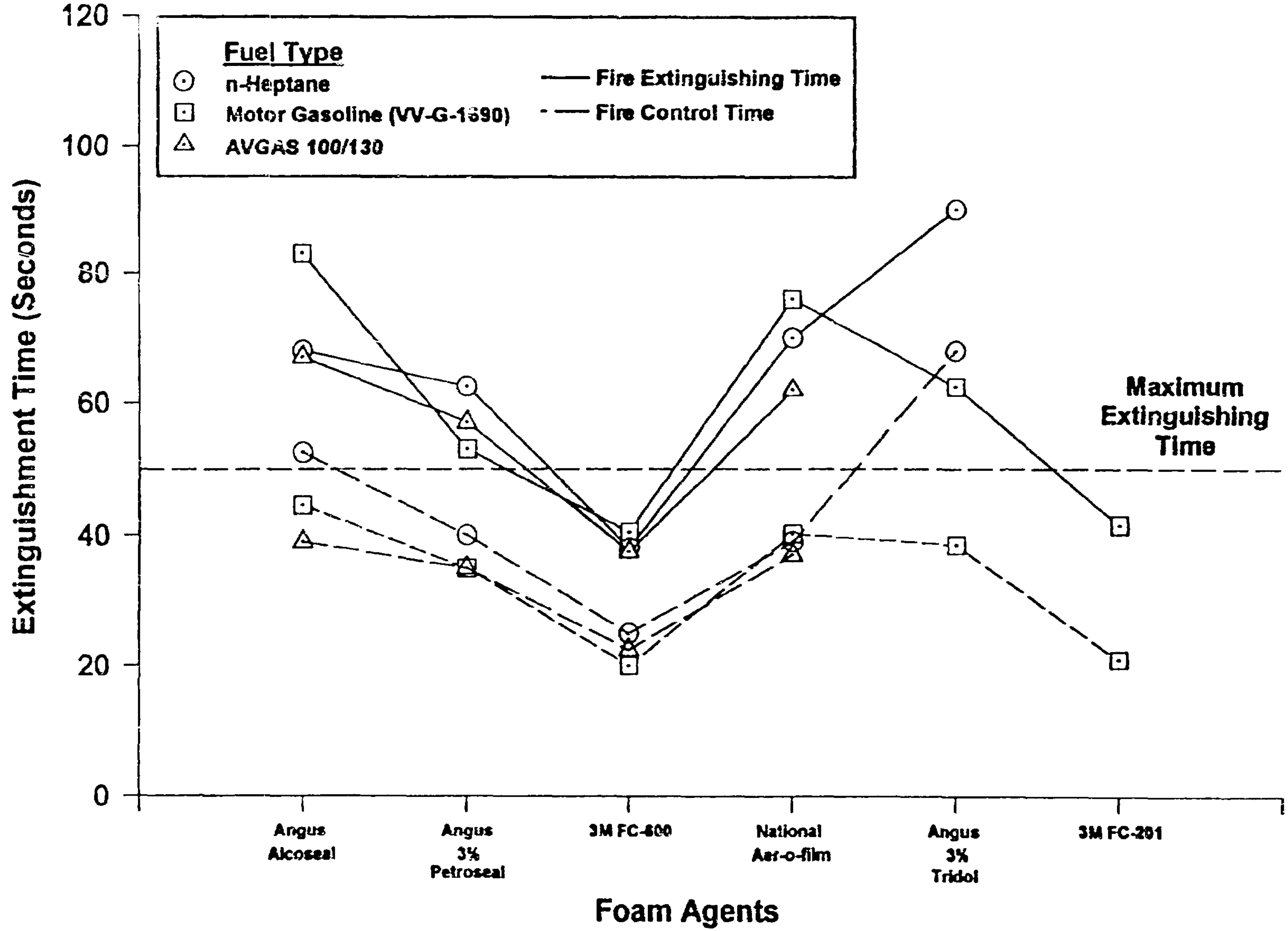

FIGURE A-3. EFFECT OF FUEL TYPE OF FIRE PERFORMANCE USING THE MIL-F-24385C 50 SQUARE FOOT FIRE TEST

From the results from these experiments, it is speculated that the spreading coefficient, which was developed by W.D. Harkins[A1] for pure liquid systems, does not apply in all cases to complex aqueous fluorocarbon systems. The oleophobicity demonstrated by the aqueous film-forming foams may be responsible, in part, for the fire extinguishing effectiveness of those agents which demonstrate a negative spreading coefficient on some test fuels.

SPREADING RATES OF AQUEOUS FLUOROCARBON FILMS ON JET A FUEL.

In the previous section, it was demonstrated that spreading coefficient alone was not a reliable indicator of fire extinguishing performance. It is believed that the extinguishing effectiveness of the film-forming foams is attributable, at least in part, to the fluidity of the foam solution on the fuel surface. The rate of spread and the stability of the aqueous film is a contributing factor in the rapid control/extinguishment characteristics of these agents on hydrocarbon fuel fires.

The FFFP concentrates contain a protein hydrolyzate as the foam stabilizer while the AFFF concentrates employ a water soluble polymer as the foam stabilizing agent. The protein derivative in the FFFP formulation tends to produce a more viscous and slower draining foam than the synthetic polymer in the AFFF composition. A knowledge of the relative film spreading rate of each aqueous film-forming composition may be of value in understanding the fire extinguishing characteristics of these agents.

A laboratory apparatus was developed for measuring the spreading rates of aqueous films on aviation fuels. This apparatus and the test procedure is described in reference A2. The film spread rate is determining by discharging four milliliters (mL) of foam solution down an inclined trough onto a pan with Jet A fuel. The foam solution is discharged at a uniform rate of 0.10 mL/s. The distance traveled by the contiguous aqueous film is recorded at appropriate time intervals.

The film spread rates obtained for the AFFF and FFFP agents on Jet A fuel are summarized in table A-4. The total distance traveled by the aqueous fluorocarbon films down the length of the trough, before lensing and breakup of the film occurred, was approximately 90 centimeters for both the AFFF and FFFP agents. Although the data do not correlate directly with the spreading coefficient of the agents with cyclohexane (different fuel), the magnitude of differences between the AFFF and FFFP spreading rates do correlate with the extinguishment data in tables 10 and 11. The spreading rate of AFFF is approximately double that of the FFFPs. The control and extinguishment times of these AFFFs were roughly 30 to 50 percent less than that of the FFFPs using the 50 ft^2 (4.6 m^2) MIL SPEC fire test.

FIRE PERFORMANCE AS A FUNCTION OF SPREADING COEFFICIENT AND FLUORINE CONTENT.

Because of the wide variation in the composition of the aqueous film-forming foam agents currently being manufactured, a comparison of agent fluorine content of the film-forming agents was conducted. Figure A-4 shows the value of the spreading coefficient (SC) as a function of the agent's fluorine content. The minimum value of the SC under Military Specification MIL-F-24385C is +3, accordingly the dashed horizontal line (figure A-4) separates those agents which meet the requirement from those which do not.

TABLE A-4. RELATIVE FILM SPREAD RATES OF THE FILM FORMING AGENTS ON JET A FUEL

Agent Type	Film Spread Rate (cm/s)
FFFP Angus Petroseal 3%	0.85
FFFP Angus Petroseal 6%	0.95
AFFF Angus Tridol 6%	2.29
AFFF NFS Aer-O-Water 6%	2.22

Tables 10 and 11 presented the fire performance for each AFFF agent shown in figure A-4 using the 50 ft^2 (4.6 m^2) fire conducted in accordance with MIL-F-24385C. Of the 18 agents tested, only eight met all of the fire test requirements of the military specification. Of the 18 agents analyzed, five had a SC below three while 12 had an SC greater than three, and one agent was considered "borderline" with an SC value of 3.01. Of the 13 agents which demonstrated an SC above three, only five passed all of the requirements of MIL-F-24385C while three of five agents with SCs below three passed all of the fire test requirements of the military specification. It can be concluded that spreading coefficient alone is not a reliable indicator of fire and burnback performance. There is also no correlation of the fluorine content with the spreading coefficient.

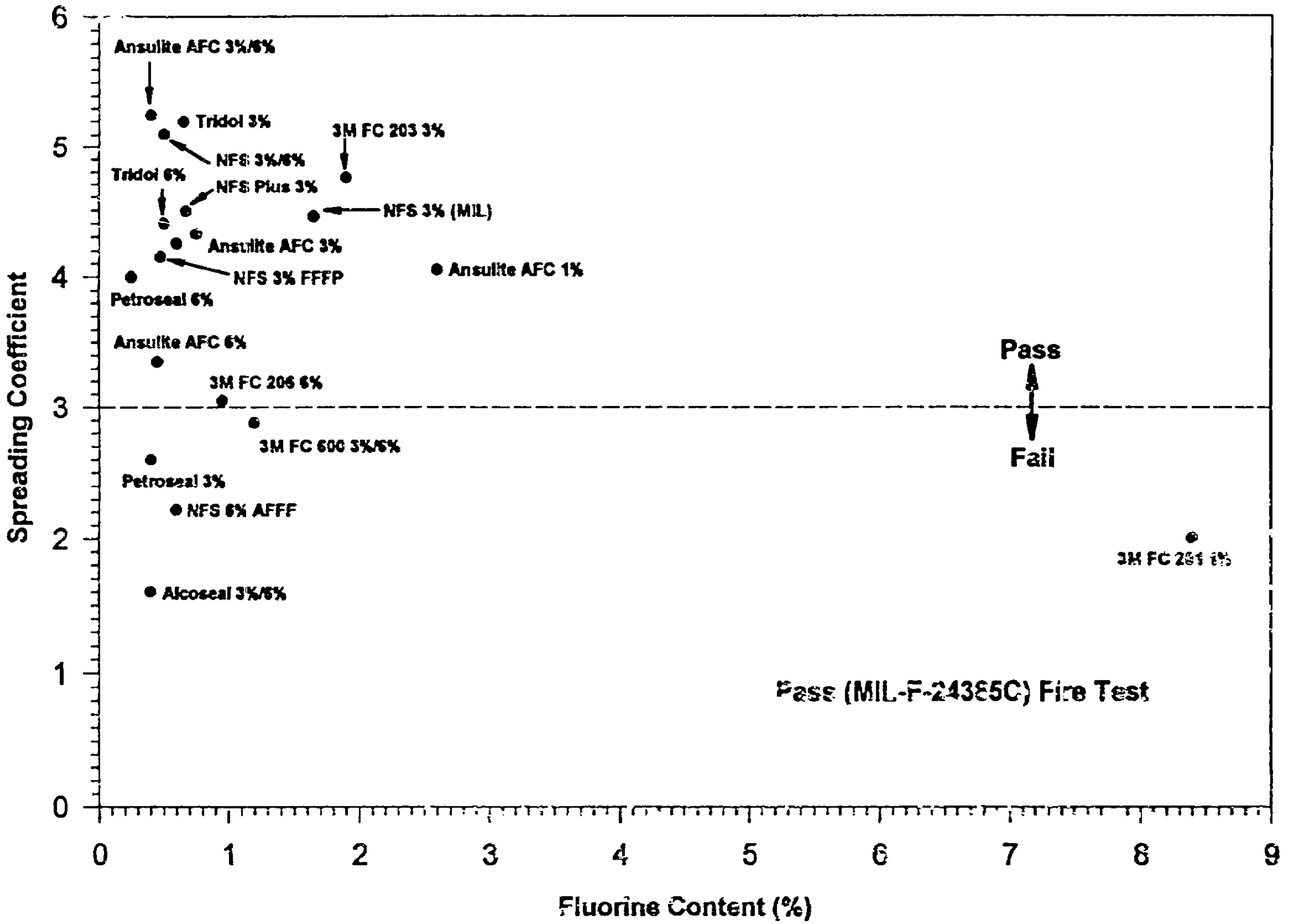

FIGURE A-4. SPREADING COEFFICIENT AS A FUNCTION OF FLUORINE CONTENT

REFERENCES

A1. Harkins, W.D., "The Physical Chemistry of Surface Films," Rheinhold Publishing Corporation, 1952.

A2. Geyer, G.B., Neri, L.M., and Urban, C.H., "Comparative Evaluation of Firefighting Foam Agents," FAA Technical Report FAA-NA-79-2, Washington, DC, August 1979.

Appendix B

Summary of NRL Tests

INTRODUCTION

Bench-scale, 28 ft^2 (2.6 m^2) and 50 ft^2 (4.6 m^2) tests were performed by NRL in accordance with Revision C of the MIL SPEC. Two AFFF agents were tested, both 6 percent products from the QPL. A commercial 6 percent FFFP product was also tested. The following is a summary of testing from the Naval Research Laboratory. For complete details and analysis, see reference 24.

EQUIPMENT AND PROCEDURES

SPREADING COEFFICIENTS.

Reagent grade cyclohexane and 99 percent pure n-heptane were used as the reference fuels. Surface tension and interfacial tension were measured in accordance with ASTM D-1331, "Standard Test Methods for Surface and Interfacial Tension of Solutions of Surface-Active Agents." A du Nouy tensiometer, having a torsion balance with a 4- or 6-cm circumference platinum-iridium ring, was lowered into the liquid and slowly pulled out until the liquid detached from the ring's surface. The force recorded at the point where this separation occurred was recorded as the surface tension (dynes/cm) of the pure liquid. Similarly, the interfacial tension was the measurement of tension when the ring was pulled through the boundary layer between two liquids.

FILM FORMATION AND SEALABILITY.

Two methods were used to measure the film formation and sealability of foams. The first method, in accordance with Revision C of the MIL SPEC, used a measured amount of expanded foam applied over a fuel bed of cyclohexane in a 1000 mL beaker. An inverted steel mesh cone was inserted in the cylinder to push away the foam from the fuel surface. Residual foam was cleared from the fuel surface in the center of the cone, and film producing liquid was allowed to seep through the mesh cone. After one minute, a pilot flame was passed over the fuel surface at a height of 0.5 in. (1.27 cm). The test method permits a small flash, but no sustained ignition of the fuel may result.

The second method used involved a flat-head wood screw placed in a petri dish filled with n-heptane. Using a microsyringe, a measured amount of unexpanded foam solution was applied to the tip of the screw at a rate of one droplet per second. Two minutes after the initiation of solution application, a pilot flame was passed over the fuel surface at a height of 0.5 in. (1.27 cm). The pass/fail criteria was the same as the Revision C criteria.

EXPANSION AND DRAINAGE.

The tests were conducted in accordance with the method outlined in the MIL SPEC, which is similar to Method A in NFPA 412. A 2 gpm (7.6 Lpm) nozzle was utilized to discharge expanded foam onto an inclined backboard. From the backboard, the foam was collected in 1000 mL graduated cylinders. After the cylinders were filled, they were removed and a timer was started. The cylinder was then cleaned off and weighed, and the total volume of solution collected in the cylinder was calculated (where 1 mL solution = 1 g solution).

The expansion ratio was determined using the following equation:

$$E.R. = \frac{1000}{W_{soln}} \qquad \text{(B1)}$$

where E.R. = expansion ratio, and
W_{soln} = weight of solution in cylinder (g).

The 25 percent drainage time is the time for 25 percent of the total liquid to drain from the foam sample. The 25 percent drainage volume was determined by using the weight of the solution in the cylinder (W_{soln} above). The 25 percent drainage time was recorded when the liquid level in the sample reached the 25 percent drainage volume. Expansion ratio and drainage time tests were conducted with both fresh and simulated sea water solutions.

FLUORINE CONTENT.

Fluorine content was determined using the ion analyzer method described in the MIL SPEC.

MIL SPEC FIRE TESTS.

Fire tests were performed with the foam agents in accordance with MIL-F-24385. For the 28 ft^2 (2.6 m^2) tests, Revision C was used. Motor gasoline in accordance with Federal Specification VV-G-1690 was used and the fresh water foam was discharged through an air aspirating nozzle at a rate of 2 gpm (7.6 Lpm). This resulted in an application rate of 0.071 gpm/ft^2 (2.9 Lpm/m^2).

In reporting the 28 ft^2 (2.6 m^2) fire test results, two nonstandard methods of determining fire knockdown were used. Both methods use the radiometer setup described for the 28 ft^2 (2.6 m^2) test in the proposed Revision D of the MIL SPEC. Radiant heat flux measurements were recorded at the 10-, 15-, 20- and 25-second time intervals. The reduction in heat flux was calculated by dividing the flux level at each time interval by the peak flux level at the time agent application was begun. This ratio was then converted to a "percent extinguished" value. The 25-second summation is the sum of these percentage values for all four time intervals.

The 90 percent control time is the time at which the radiant flux was reduced to a level which corresponds to a 90 percent decrease in fire area. The method of calculation is similar to that used to determine the 25 s summation value, except that the calculations are performed for all data points starting at the start of agent application. A detailed description of these estimating techniques is contained in reference 24.

The burnback resistance for the 28 ft^2 (2.6 m^2) test is described by the 15 percent burnback time. This time was also calculated from radiometer data collected during the test. It is based on a 300 percent increase in flux level over an initial background level. The initial background flux level is determined by averaging the values recorded for the time period 1 to 3 min after the burnback pan was lit. As the test progressed, the flux level was continually checked. When the flux level reached a value that was 300 percent greater than the initial background value, the time was recorded as the 15 percent burnback time.

The 50-ft^2 (4.6 m^2) fire tests were performed in accordance with Revision C of the MIL SPEC. Seawater foam solutions were discharged through the 2-gpm (7.6 Lpm) nozzle on motor gasoline and n-heptane fires. The resulting application rate was 0.04 gpm/ft^2 (1.6 Lpm/m^2). The 40 second summation was the sum of the percent fire area extinguished at 10, 20, 30 and 40 seconds after the initiation of firefighting. Twenty-five percent burnback time was recorded as the time when 25 percent of the test area was reinvolved in fire after the burnback pan was placed in the pool.

NONAIR-ASPIRATED NOZZLE TEST.

The nonair-aspirated test was performed using a 50-ft^2 (4.6 m^2) n-heptane pool fire. A nonair-aspirating spray nozzle, Grinnell Model D4A, was modified with an orifice plate to flow 5.5 gpm (20.8 Lpm). This resulted in an application rate of 0.11 gpm/ft^2 (4.6 Lpm/m^2). This nozzle is normally used as a fixed water-spray nozzle. The expansion and drainage characteristics were determined using the test method described in the MIL SPEC, substituting the D4A nozzle flowing 5.5 gpm (20.8 Lpm) for the MIL SPEC 2-gpm (7.6 Lpm) nozzle. The 50-ft^2 (4.6 m^2) fire was attacked manually by a firefighter. The attack was aggressive until approximately 90 percent control was achieved. At that time, the nozzle was backed off so that there was a gentler application. The fire was totally extinguished by allowing the foam to spread and fill in the remaining fire area with no direct application to the flaming area. The subsequent burnback test followed the 50-ft^2 (4.6 m^2) MIL SPEC test procedure. Agent application time totalled 90 s.

RESULTS AND ANALYSIS

SPREADING COEFFICIENTS.

The values for surface tension, interfacial tension, and spreading coefficient are presented in table B-1. The AFFF had a higher surface tension and a lower interfacial tension, compared to the FFFP. The commercial FFFP had a negative spreading coefficient when tested with n-heptane. No across-the-board correlations between spreading coefficients, fire control, extinguishment, and burnback resistance are apparent. As such, the spreading coefficient data alone cannot be used as relative predictors of fire performance.

FILM FORMATION AND SEALABILITY TESTS.

The results of the Film Formation and Sealability tests are presented in table B-2. For both procedures, an agent was considered to have passed if the pilot flame could be moved one time slowly from one side of the dish or container to the other and then back again, without producing sustained ignition. If ignition did not occur, the flame passage over the fuel surface was continued 4-5 times or until ignition occurred.

TABLE B-1. SPREADING COEFFICIENTS

Agent	Surface Tension (dynes/cm)	Interfacial Tension (dynes/cm)	Spreading Coefficient
with cyclohexane			
MIL SPEC AFFF #2	17.45	1.80	5.40
Commercial FFFP	16.71	5.42	2.52
with n-heptane			
MIL SPEC AFFF #2	17.45	2.16	0.04
Commercial FFFP	16.71	5.51	2.57
Fuels			
Cyclohexane	24.65		
n-heptane	19.65		

TABLE B-2. RESULTS OF FILM FORMATION AND SEALABILITY TESTS

Agent	Test Fuel	Results	Number of Passes with Flame to Ignite
MIL SPEC 6% AFFF #2	n-heptane Cyclohexane	passed passed	2 NI
Commercial FFFP	n-heptane Cyclohexane	failed passed	<1 NI

NI = sustained ignition did not occur after 4-5 passes of the flame.

In tests conducted in accordance with the Revision C test procedure, all of the agents passed. In no case was ignition sustained with 4-5 passes of the flame. This was expected since the spreading coefficients of all the agents on cyclohexane were significantly positive (all >2.5). This clearly demonstrates the ability of the agents to produce a film (on cyclohexane) from solution draining out of the expanded foam blanket, an important characteristic if the foam blanket is disturbed.

In the n-heptane test, the spreading coefficient of the commercial FFFP was negative (-2.67). The FFFP did not pass the modified film and seal test using n-heptane film and seal test.

EXPANSION RATIO AND DRAINAGE TIME.

The expansion ratio and 25 percent drainage time values are used to characterize the quality of the foam produced. The expansion ratio is a measure of the solution's ability to form a stable bubble structure from entrained air. Drainage time is a measure of how durable the bubble structure is and the rate at which solution is being released from the bubbles. These values obtained in expansion and drainage testing for a given agent are dependent on the discharge device, collection method, temperature of the agent, type of water used to mix the solution, and the configuration of the collection container.

The results of the expansion ratio and 25 percent drainage time tests are presented in table B-3. Data are given for both fresh water and simulated sea water solutions. Drainage time is important to burnback resistance since it is the foam blanket which supplies the film forming solution to the fuel surface. If the foam blanket breaks down too quickly, then the film is exposed to the reignition source and evaporates. The relative rankings of the agents based on fresh water 25 percent drainage times and 28 ft^2 fire burnback test results correspond with one another.

TABLE B-3. EXPANSION AND DRAINAGE TEST RESULTS FOR FRESH AND SALT WATER SOLUTIONS

Agent	Fresh Water		Seawater	
	Expansion Ratio (:1)	25% Drainage Time (s)	Expansion Ratio (:1)	25% Drainage Time (s)
MIL SPEC AFFF				
MIL SPEC #1	7.5	288	7.5	238
	7.8	281	7.5	248
	7.7	301	8.2	301
	7.7	253	8.5	270
	7.7	265	--	--
	7.8	283	--	--
Averages	7.7	278.5	7.9	270.0
MIL SPEC #2	7.4	271	7.2	251
	7.7	280	7.1	269
	7.7	255	7.7	211
	7.4	288	7.8	245
	8.2	242	--	--
	8.4	266	--	--
Averages	7.8	267.0	7.5	244.0
FFFP				
Commercial FFFP	7.4	283	7.2	254
	6.6	249	7.2	257
	7.0	236	7.1	264
	7.2	214	6.6	257
Averages	7.1	245.5	7.0	258.0

FLUORINE CONTENT.

The intent of the requirement in the MIL SPEC to report fluorine content is to provide a quality control measurement for purchasing purposes. There is currently no minimum fluorine content requirement contained in the MIL SPEC. The fluorine content of a product is determined at the time of qualification, and is then checked for each lot to be purchased. The type of fluorosurfactant will impact on fire test results as significantly as the amount will. Table B-4 reports the results of fluorine content. It can be seen that there is no direct correlation between fluorine content and extinguishment performance or burnback resistance. This is in agreement with the findings by the FAA.

TABLE B-4. FLUORINE CONTENT OF AFFF AND FFFP

Fluorine Content by Weight	Agent Description
0.11	6% FFFP, Commercial FFFP, purchased in 1989
0.61	MIL SPEC Agent #1, Date of Manufacturer: 5/1985, Lot 557
0.42	MIL SPEC Agent #2, Date of Manufacture: 10/1988, Lot X18044

MIL SPEC FIRE TESTS.

Fire test results are reported in tables B-5 and B-6. Extinguishment application density, which normalizes the results by eliminating the time element, is used for comparative purposes. The data show that across the board the average 90 percent control, 100 percent extinguishment, and 25 percent burnback times for the MIL SPEC agents are superior to the commercially available FFFP agent tested. The knockdown times, represented by 90 percent control and the 25- and 40-second summation values, are relatively close. In the 28 ft^2 (4.6 m^2) and 50 ft^2 (2.6 m^2) n-heptane tests, the relatively small absolute differences in 100 percent extinguishment times (9-15 seconds) result in large (31 percent) differences in extinguishment application densities. The burnback performance of the AFFFs in the 50 ft^2 (2.6 m^2) and 50 ft^2 (4.6 m^2) n-heptane test series exceed the FFFP by 17-30 percent. These data are consistent with the previously unreported NRL data (reference 24) and the FAA data.

NON-ASPIRATED NOZZLE TEST.

The results of the nonaspirated test are shown in table B-7. The test was found to be a very challenging fire, particularly in terms of total extinguishment. With both AFFF and FFFP, there were test runs where the fire was not totally extinguished after 90 seconds of agent application.

In the tests where total extinguishment was achieved, the data show that knockdown times, as indicated by the 40 s summation value, are nearly the same, and that the AFFF had a better extinguishment time. With the FFFP, the fire was not extinguished until the agent was shut off and the foam sealed the remaining fire. AFFF again showed better burnback resistance. These tests showed that FFFP can be used through a nonair-aspirated discharge device to extinguish a hydrocarbon pool fire. Again, MIL SPEC AFFF was superior in terms of fire control, extinguishment, and burnback resistance.

TABLE B-5. REVISION C MIL SPEC 28 ft^2 (50 m^2) Fire Tests with MIL SPEC AFFF AGENTS AND FFFP[a]

Agent	25 s Summation	90% Control Time (s)	Observed 100% Extinguishment Time (s)	Calculated 15% Burnback Time (s)	Extinguishment Application Density (gal/ft^2 (L/m^2))
MIL SPEC AFFF #1	312	16	23	--[b]	0.027 (1.12)
	343	16	24	514	0.029 (1.16)
	310	17	23	563	0.027 (1.12)
	326	16	24	552	0.029 (1.16)
MIL SPEC AFFF #2	317	16	27	531	0.032 (1.31)
	311	17	29	514	0.035 (1.41)
Overall Averages	320	17	27	540	0.032 (1.31)
Commercial FFFP[b]	277	21	36	419	0.043 (1.75)
	252	21	35	412	0.042 (1.70)
Average	264.5	21.0	35.5	415.5	0.042 (1.72)

[a] Tests were conducted with Mogas and fresh water solutions.
[b] Test not performed because excessive foam blanket depth extinguished fire in burnback pan.

TABLE B-6. MIL SPEC 50 FT^2 (4.6 M^2) FIRE TESTS

Agent	40 s Summation (%)	100% Extinguishment Time (s)	Observed 25% Burnback Time (s)	Extinguishment Application Density (gal/ft^2 (L/m^2))
with Mogas				
MIL SPEC AFFF #2 (Average of 4 Tests)	318	53	374	0.035 (1.43)
Commercial FFFP (Average of 2 Tests)	295	55	354	0.037 (1.49)
with n-heptane				
MIL SPEC AFFF #2 (Average of 4 Tests)	319	48	450	0.032 (1.29)
Commercial FFFP	315	63	383	0.042 (1.71)

TABLE B-7. NONAIR-ASPIRATED NOZZLE TESTS
(n-heptane, 50 ft^2 (4.6 m^2), 5.5 gpm (20.1 Lpm), 0.11 gpm/ft^2 (4.5 Lpm/m^2))

Agent	40 s Summation (%)	100% Extinguishment Time (s)	25% Burnback Time (s)
MIL SPEC AFFF #2	225	73	351
Commercial FFFP	205	93	281

Appendix C

Small- and Large-scale Test Data

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS

Foam	Application Rate (gpm/ft^2)	Test Area (ft^2)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft^{-2})	Control Application Density (gal/ft^2)	Reference
AFFF	0.02	3525	JP-5	NAA	38	0.0108	0.013	Darwin
AFFF	0.02	3525	JP-5	AA	39	0.0111	0.013	Darwin
AFFF	0.02	3525	JP-5	AA	32	0.0091	0.011	Darwin
AFFF	0.02	4000	JP-4	NAA	21	0.0053	0.007	Jablonski
AFFF	0.02	9000	JP-5	AA	46	0.0051	0.015	Tuve
AFFF	0.03	4,000	JP-4	AA	30	0.0075	0.015	Jablonski
AFFF	0.03	8,000	JP-4	NAA	61	0.0076	0.031	FAA-AFFF
AFFF	0.03	9,000	JP-5	AA	37	0.0041	0.019	Tuve
AFFF	0.03	10,580	JP-5	AA	66[a]	0.0062	0.033	Darwin
AFFF	0.03	15,386	JP-4	AA	70	0.0045	0.035	FAA-AGFSRS
Protein	0.03	9,000	JP-5	AA	42	0.0047	0.021	Tuve
AFFF	0.04	50	Gasoline	AA	25.6[a]	0.5120	0.017	Scheffey
AFFF[b]	0.04	50	Avgas	AA	32	0.6400	0.021	Scheffey
FFFP	0.04	50	Gasoline	AA	38.6[a]	0.7720	0.026	Scheffey
AFFF	0.04	4,400	JP-5	AA	44	0.0100	0.029	Tuve
AFFF	0.04	4,400	Avgas	AA	38	0.0086	0.025	Tuve
AFFF	0.04	6,241	Jet A	AA	26	0.0042	0.017	FAA

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS (Continued)

Foam	Application Rate (gpm/ft^2)	Test Area (ft^2)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft^{-2})	Control Application Density (gal/ft^2)	Reference
FFFP	0.04	6,241	Jet A	AA	35	0.0056	0.023	FAA
AFFF	0.04	8,000	JP-4	NAA	24	0.0030	0.016	Jablonski
AFFF	0.05	8,000	JP-4	NAA	58[a]	0.0073	0.048	FAA-AFFF
AFFF	0.05	8,000	JP-4	AA	36.5	0.0046	0.030	Jablonski
AFFF	0.05	8,000	JP-4	AA	44.5	0.0056	0.037	FAA-AFFF
AFFF	0.05	6,000	JP-5	AA	46	0.0077	0.038	FAA-AFFF
AFFF	0.05	8,000	Avgas	AA	56	0.0070	0.047	FAA-AFFF
AFFF	0.05	15,386	JP-4	AA	62	0.0040	0.052	FAA-AGFSRS
AFFF	0.05	16,000	Jet A	AA	28[a]	0.0018	0.023	FAA-COMP
AFFF	0.05	16,000	Jet A	NAA	24[a]	0.0015	0.020	FAA-COMP
FPF	0.05	16,000	Jet A	AA	54[a]	0.0034	0.045	FAA-COMP
P	0.05	15,386	JP-4	AA	118	0.0077	0.098	FAA-AGFSRS
P	0.05	16,000	Jet A	AA	46[a]	0.0029	0.038	FAA-COMP
FPF	0.06	50	Gasoline	AA	98[a]	1.9600	0.098	FAA
AFFF	0.06	1,000	Avgas	NAA	17[a]	0.0170	0.017	NRL
AFFF[b]	0.06	1,000	Avgas	NAA	16	0.0160	0.016	Scheffey
AFFF[b]	0.06	1,000	Avgas	NAA	26	0.0260	0.026	Scheffey

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS (Continued)

Foam	Application Rate (gpm/ft²)	Test Area (ft²)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft²)	Control Application Density (gal/ft²)	Reference
AFFF	0.06	3,525	JP-5	AA	28	0.0079	0.028	Darwin
P	0.06	3,525	JP-5	AA	35[a]	0.0099	0.035	Darwin
AFFF	0.06	4,000	JP-4	AA	45[a]	0.0113	0.045	FAA-AFFF
AFFF	0.06	4,400	Avgas	AA	19	0.0043	0.019	Tuve
AFFF	0.06	4,400	JP-5	AA	18	0.0041	0.018	Tuve
P	0.06	4,400	JP-5	AA	25	0.0057	0.025	Tuve
P	0.06	4,400	Avgas	AA	57	0.0130	0.057	Tuve
AFFF	0.06	7,850	JP-4	AA	40	0.0051	0.040	FAA-AGFSRS
AFFF[b]	0.06	431	Gasoline	AA	73[a]	0.1694	0.073	SRDB
FFFP	0.06	431	Gasoline	AA	76[a]	0.1763	0.076	SRDB
P	0.06	7,850	JP-4	AA	65	0.0083	0.065	FAA-AGFSRS
AFFF	0.07	28	Gasoline	A	17.3[a]	0.6179	0.020	Scheffey
AFFF[b]	0.07	28	Avgas	AA	23	0.8214	0.027	Scheffey
AFFF[b]	0.07	28	Avgas	AA	26	0.9286	0.030	Scheffey
FFFP	0.07	28	Gasoline	A	27	0.9643	0.032	Scheffey
P	0.10	50	Gasoline	AA	75[a]	1.5000	0.125	FAA
AFFF[b]	0.10	602	Gasoline	AA	51[a]	0.0847	0.085	Johnson

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS (Continued)

Foam	Application Rate (gpm/ft²)	Test Area (ft²)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft⁻²)	Control Application Density (gal/ft²)	Reference
AFFF[b]	0.10	602	Gasoline	AA	51[a]	0.0847	0.085	Johnson
FFFP	0.10	602	Gasoline	AA	58[a]	0.0963	0.097	Johnson
FFFP	0.10	602	Gasoline	AA	63[a]	0.1047	0.105	Johnson
AFFF	0.10	2,500	Jet A	AA	9.5[a]	0.0038	0.016	FAA
FFFP	0.10	2,500	Jet A	AA	8.6[a]	0.0034	0.014	FAA
AFFF	0.10	2,666	JP-4	AA	36[a]	0.0135	0.060	FAA-AFFF
AFFF	0.10	2,666	JP-5	AA	52	0.0195	0.087	FAA-AFFF
AFFF	0.10	2,666	Avgas	AA	52	0.0195	0.087	FAA-AFFF
AFFF	0.10	3,525	Avgas	AA	43[a]	0.0122	0.072	Darwin
AFFF	0.10	3,525	JP-4	AA	35[a]	0.0099	0.058	Darwin
AFFF	0.10	4,000	JP-4	AA	36.5[a]	0.0091	0.061	FAA-AFFF
AFFF	0.10	4,000	JP-4	NAA	38[a]	0.0095	0.063	FAA-AFFF
AFFF	0.10	7,850	JP-4	AA	21[a]	0.0027	0.035	FAA-AGFSRS
FPF	0.10	7,850	JP-4	AA	35	0.0045	0.058	FAA-AGFSRS
P	0.10	7,850	JP-4	AA	41	0.0052	0.068	FAA-AGFSRS
AFFF	0.10	8,000	Jet A	AA	16.5[a]	0.0021	0.028	FAA-COMP
AFFF	0.10	8,000	Jet A	NAA	16[a]	0.0020	0.027	FAA-COMP

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS (Continued)

Foam	Application Rate (gpm/ft^2)	Test Area (ft^2)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft^2)	Control Application Density (gal/ft^2)	Reference
FPF	0.10	8,000	Jet A	AA	21[a]	0.0026	0.035	FAA-COMP
P	0.10	8,000	Jet A	AA	20.5[a]	0.0026	0.034	FAA-COMP
AFFF	0.13	3,846	JP-4	AA	35	0.0091	0.076	FAA-AGFSRS
P	0.13	3,846	JP-4	AA	58	0.0151	0.126	FAA-AGFSRS
AFFF	0.15	1,666	JP-4	AA	29[a]	0.0174	0.073	FAA-AFFF
AFFF	0.15	1,666	JP-5	AA	35	0.0210	0.088	FAA-AFFF
AFFF	0.15	1,666	Avgas	AA	51	0.0306	0.128	FAA-AFFF
AFFF	[illegible].5	4,000	JP-4	AA	24.5[a]	0.0061	0.061	FAA-AFFF
AFFF	0.18	1,400	JP-5	AA	8.5[a]	0.0061	0.026	Tuve
AFFF	0.18	1,400	Avgas	AA	14	0.0100	0.042	Tuve
P	0.18	1,400	JP-5	AA	11[a]	0.0079	0.033	Tuve
P	0.18	1,400	Avgas	AA	22	0.0157	0.066	Tuve
AFFF	0.20	315	JP-5	AA	8	0.0254	0.027	Darwin
AFFF	0.20	3,846	JP-4	AA	21	0.0055	0.070	FAA-AGFSRS
P	0.20	3,846	JP-4	AA	25	0.0065	0.083	FAA-AGFSRS
AFFF	0.36	700	Avgas	AA	9	0.0129	0.054	Tuve

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

TABLE C-1. SUMMARY OF TEST DATA USED FOR CORRELATION BETWEEN SMALL- AND LARGE-SCALE TESTS (Continued)

Foam	Application Rate (gpm/ft^2)	Test Area (ft^2)	Fuel	Nozzle (AA/NAA)	Control Time (s)	Specific Control Time (s-ft^{-2})	Control Application Density (gal/ft^2)	Reference
AFFF	0.36	700	JP-5	AA	6	0.0086	0.036	Tuve
P	0.36	700	Avgas	AA	12	0.0171	0.072	Tuve
P	0.36	700	JP-5	AA	9	0.0129	0.054	Tuve

[a] Average of multiple tests
[b] Non-MIL SPEC AFFF

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